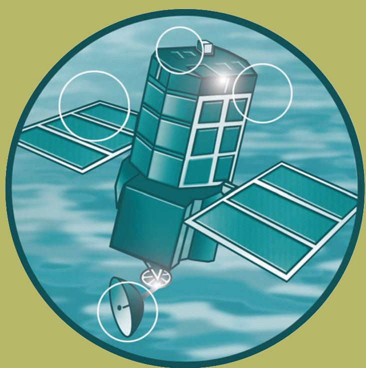
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Development and Demonstration of Systems Based Estuary Simulators (EstSim)

EstSim Behavioural Statements Report

R&D Project Record FD2117/PR2



Environment Agency

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Development and Demonstration of Systems Based Estuary Simulators (EstSim)

Behavioural Statements Report

Prepared by ABP Marine Environmental Research Ltd for the Estuaries Research Programme (ERP Phase 2) within the Defra and Environment Agency Joint Broad Scale Modelling Theme

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Statement of Use
This document provides information for the Department for Environment Food and Rural Affairs (Defra) and Environment Agency Staff (EA), researchers and consultants about the research project Development and Demonstration of Systems Based Estuary Simulators (EstSim) and constitutes an R&D output from the Joint Defra/Environment Agency Flood and Coastal Defence R&D Programme (Estuaries Research Programme Phase 2).

Contract Statement
This report describes work commissioned by Defra under Project FD2117 Development and Demonstration of Systems Based Estuary Simulators (EstSim). The Funders Nominated Project Officer was Kate Scott Environmental Agency. (Email: Kate.Scott@environment-agency.gov.uk.) The ABPmer Project Number was R/3434 and the Project Manager at ABPmer was Alun Williams (Email: awilliams@abpmer.co.uk).

Collaboration Statement
This report was prepared by the EstSim Consortium comprising: ABP Marine Environmental Research Ltd (lead), University of Plymouth (School of Engineering), University College London (Coastal & Estuarine Research Unit), HR Wallingford, WL | Delft Hydraulics and Discovery Software.

Keywords
Behaviour, Estuary, Geomorphology, Modelling, Morphology, Systems approach.

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EXECUTIVE OVERVIEW OF FD2117: DEVELOPMENT AND DEMONSTRATION OF SYSTEMS BASED ESTUARY SIMULATORS (EstSim)

Behavioural Statements Report, April 2007

Purpose

The Broad Scale Modelling Theme of the Defra/EA Joint Thematic R&D Programme for Flood & Coastal Defence has funded three contracts under the Estuaries Research Programme, Phase 2 (FD2107, FD2116 and FD2117). FD2117 (EstSim) started in April 2004 and has the following headline aims:

- To extend the ability to simulate estuary response to change.
- Facilitate knowledge exchange through accessibility of simulation results.

The Project

ABPmer, University College London, University of Plymouth, HR Wallingford, WL│Delft Hydraulics and Discovery Software are undertaking the project. The project is of 3 years duration (April 2004 - April 2007) and has nine Scientific Objectives as follows:

1. **System Conceptualisation**: Boundary setting and focusing of research effort.
2. **Development of Management Questions**: Rationalisation of management questions that can be informed through application of systems approach.
3. **Development of Behavioural Statements**: Formal definition of estuarine system in terms of systems approach and behavioural statements.
4. **Mathematical Formalisation**: Development of behavioural statements into a logically consistent mathematical framework.
5. **Development of System Simulation**: Development of architecture for estuary simulation based on the mathematical formulation of the system definition.
6. **Manager System Interface**: Explore the use of decision support systems and visualisation techniques for proof of concept testing.
7. **Pilot Testing**: Performance evaluation of estuary simulator.
8. **Dissemination**: Increase awareness of function and utility of research.
9. **Peer Review**: Ensure research lines deliver against Scientific Objectives.

This report follows on from the Conceptualisation Stage (PR1) to develop formal definitions of estuarine systems within Scientific Objective 3 (Behavioural Statements).

In developing formal definitions a number of stages have been undertaken, including:

- Review of systems based approach as a means of capturing formal representation and behavioural concepts.
- Development of estuary typology and classification based on component geomorphological elements.
- Systems mapping of geomorphological elements within estuary types.
- Systems mapping of sub-systems within geomorphological elements.
- Behavioural descriptions of estuary type and geomorphological elements.

The examination of estuary typology identified seven estuary behavioural types, including:

- Fjord;
- Fjard;
- Ria;
- Spit-enclosed drowned river valley;
- Funnel-shaped drowned river valley;
- Embayment, and
- Tidal inlet.

Each estuary behavioural type can be uniquely identified dependant upon antecedent conditions and the component geomorphological elements. Eleven geomorphological elements were used to define relationships and interactions within estuary types, including:

- Cliffs;
- Barrier Beach;
- Spits;
- Dunes;
- Deltas;
- Rock Platform;
- Channel;
- Mudflat;
- Sandflat;
- Saltmarsh, and
- Drainage Basin.

This report will be used to guide the mathematical formalisation of the systems descriptions to develop behavioural models in the next stage in the EstSim project (Scientific Objective 4).

Contact Details
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1. INTRODUCTION

1.1 Background

On 1 April 2004 ABP Marine Environmental Research Ltd (ABPmer) and its Project Partners were awarded research contract FD2117 (CSA 6064) within the Broad Scale Modelling Theme of the Defra/EA Joint Thematic R&D Programme for Flood & Coastal Defence.

The contract for FD2117 was awarded on the basis of a 'contract won in competition' after submission of a CSG7 (revised CSG7 submitted on 8 March 2004).

Entitled 'Development and Demonstration of Systems-Based Estuary Simulators' (hereafter EstSim), this research contract forms one of three contracts awarded under Phase 2 of the Estuary Research Programme (ERP). The two other contracts under the umbrella of ERP Phase 2 are (i) FD2107: Development of Estuary Morphological Models, and (ii) FD2116: Review and Formalisation of Geomorphological Concepts and Approaches.

The three phases of the Estuaries Research Programme seek to improve our understanding and prediction of estuarine morphological change over the medium to long-term, thereby facilitating strategic and sustainable decisions regarding flood and coastal defence.

The EMPHASYS Consortium undertook Phase 1 of this programme by evaluating existing morphological modelling approaches with the most promising of these approaches being developed within ERP Phase 2. It is anticipated that Phase 3 will seek to incorporate prior ERP research into an 'Integrated Estuary Management System'.

1.2 Project Aims

The overall aim of EstSim is to extend the ability to simulate estuarine response to change. This will be achieved through the delivery of research into the systems-based approach as an alternative yet complementary methodology to those research lines being undertaken within the other ERP Phase 2 projects (morphological concepts, bottom-up, top-down and hybrid methods). EstSim will also explore the simulation process in order to facilitate knowledge exchange between the systems-based tools and estuary managers. Integration of the systems based approach and existing methods is shown conceptually within Figure 1.

1.3 Project Structure

The project has been structured in to nine Scientific Objectives, covering the required lines of research and dissemination:

1. **System Conceptualisation**: Boundary setting and focusing of research effort.
2. **Development of Management Questions**: Rationalisation of management questions that can be informed through application of systems approach.
3. **Development of Behavioural Statements**: Formal definition of estuarine system in terms of systems approach and behavioural statements.
4. **Mathematical Formalisation**: Development of behavioural statements into a logically consistent mathematical framework.

5. **Development of System Simulation**: Development of architecture for estuary simulation based on the mathematical formulation of the system definition.
6. **Manager System Interface**: Explore the use of decision support systems and visualisation techniques for proof of concept testing.
7. **Pilot Testing**: Performance evaluation of estuary simulator.
8. **Dissemination**: Increase awareness of function and utility of research.
9. **Peer Review**: Ensure research lines deliver against Scientific Objectives.

1.4 Project Progress

Scientific Objective 1 was delivered through production of the project Inception/ Conceptualisation Report (PR1). Holding a Conceptualisation Workshop between EstSim Project Partners on 24 June 2004 facilitated this. PR1 captured the findings from that Workshop and presented a work plans for the initial stages of research.

Following the completion of PR1, work was commenced on Objective 3.

1.5 Behavioural Statements (Objective 3)

The aim of Objective 3 (Behavioural Statements) is to develop a formal definition of an estuarine system(s). The Project Inception report (FD2117/PR1) highlighted that this formal definition would require mapping out of the geomorphological sub-systems that are to be included as part of the estuary system (elements, processes and linkages), an exploration of systems diagrams and their ability to encapsulate different types of behavioural response, and development of behavioural statements (geomorphological descriptions).

In order to deliver this research a number of sub-tasks were defined. These Tasks were reviewed and re-focussed as part of the Conceptualisation Stage (Table 1).

Table 1. Objective 3 Tasks

Task	Description
3.1	Cross-reference alternative estuary classification schemes against UK estuaries in order to identify (i) classification types for main UK estuaries, and (ii) the range of geomorphic elements present in these estuaries.
3.2	For the estuarine geomorphic elements identified in Task 3.1, produce generic behavioural descriptions that include definitions of the links to driving physical processes and other elements.
3.3	Review methods of presenting systems approach to identify suitable techniques and options for estuaries and specific geomorphological elements.
3.4	Produce systems diagrams for geomorphic elements.
3.5	Develop framework that links generic geomorphic elements, their behavioural description and their systems diagrams to the behaviour of specific estuaries over the short, medium and long term.
3.6	Populate behaviour framework with two specific case estuaries (to be agreed).
3.7	Document Protocol for developing estuary behavioural statements based on above tasks.
3.8	Produce Interim Technical Report on findings and disseminate to Partners
3.9	Hold Translation Workshop where Partners can formulate and disseminate initial strategy regarding Mathematical Formulation and System Simulation
3.10	Iterate approach to systems development and produce final Technical Report

Delivery of this final Technical Report effectively completes all tasks required under Objective 3, as listed in Table 1. This document constitutes Project Record PR2 and as such is submitted in as Primary Milestone 03/02.

1.6 Follow-on Research

The production of Behavioural Statements and Systems Diagrams for estuarine geomorphological elements (Objective 3) effectively encapsulates the methodologies presented for Futurecoast (Futurecoast, 2002) but applied to estuaries.

The role of this research is to allow an examination of how the systems based approach can facilitate development of estuarine behavioural modelling. The next stage in the EstSim project will be to examine the formalisation of the systems based approach (Objective 4).

1.7 Report Structure

The report has been structured to capture the main tasks but re-ordered for ease of presentation and review, as follows:

- Section 2: Estuary Classification Scheme.
- Section 3: Review of Systems Approach.
- Section 4: Protocol
- Section 5: Estuary Type Descriptions.
- Section 6: Case Study Behavioural Statements
- Section 7: EstSim Utility
- Section 8: The Way Forwards (Future Objectives).
- Appendices A-K (Behavioural Statements and Systems Diagrams)
- Appendices L and M (Case study Behavioural Statements)

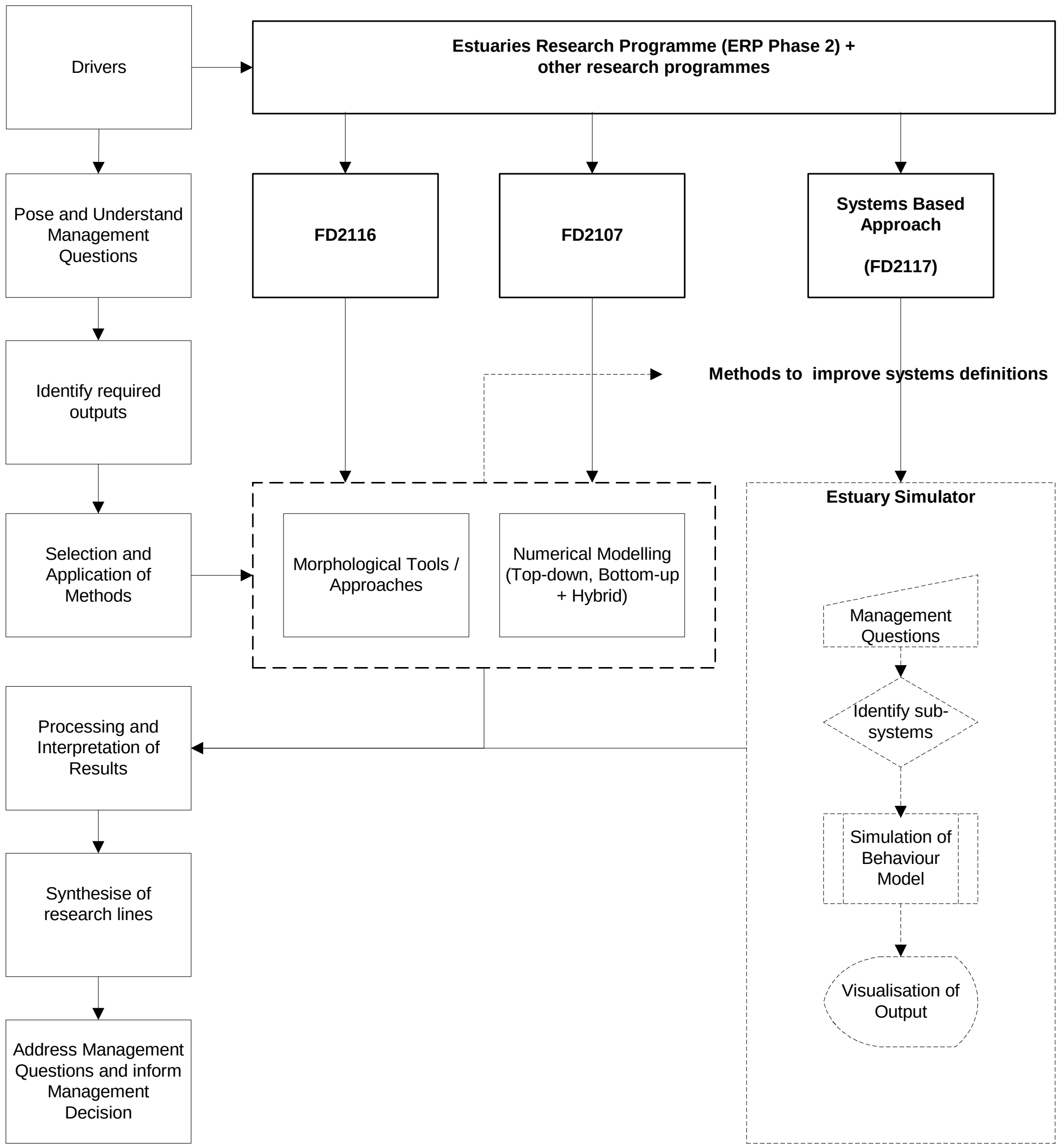


Figure 1. Integration of systems based approach

2. ESTUARY CLASSIFICATION SCHEME

2.1 Estuary Typology

Within the EstSim project the purpose of classifying estuaries is to identify the range of geomorphological elements present within each behavioural type. This provides a starting point for producing behavioural descriptions and systems diagrams of each geomorphic element and taking forwards a systems approach to understanding change in estuaries.

The categorisation of estuaries can make use of many systems, including those based on, origin, physical processes (tidal range and stratification) and characteristic geomorphological components. A number of recent classification schemes have been examined, including those of Hume & Herdendorf (1988) and Davidson (1991). Of particular relevance is the recent work undertaken by Dyer within the Futurecoast Consortium (Futurecoast, 2002). The classification produced by Dyer is shown in Table 2.

Table 2. Estuary Classification Scheme (Dyer, Futurecoast, 2002)

Type	Origin	Behavioural Type	Sub-Type
1a	Glacial valley	Fjord	With spits
1b			No spits
2a		Fjard	With spits
2b			No spits
3a	Drowned river valley	Ria	With spits
3b			No spits
4a		Spit Enclosed	Single spit
4b			Double spit
4c			Filled valley
5		Funnel shaped	
6		Embayment	
7a	Drowned coastal plain	Tidal inlet	Symmetrical
7b			Asymmetrical

This classification (Table 2) has been amended and simplified to provide a working typology with which to progress the study for UK estuaries (Table 3).

In particular, types (a) and (b) have been merged because these simply distinguish the presence of one geomorphological unit (spits). The filled valley has been omitted as a distinct type, since all estuaries have been subject to greater or lesser infilling over the Holocene and this simply reflects a particular state of a Type 4 estuary.

In terms of geomorphological elements, Table 3 combines the elements identified in Futurecoast with those defined at the first FD2117 workshop. Specific amendments include the removal of shallow subtidal as this is not really geomorphologically an independent unit; the low water channel, as this is just a variant of the ebb/flood channel (i.e. it dries); and also cheniers because they can be considered as a sub-component of mudflat and saltmarsh systems. The table then identifies which geomorphological elements are potentially present in the different types of estuary. Descriptions of the different types of estuary are expanded on in Section 5 and geomorphological elements are discussed individually in the Appendices (A-K).

Table 3. Estuary Typology

Type	Origin	Behavioural Type	Spits[1]	Barrier Beach	Dune	Delta	Linear Banks[2]	Channels[3]	Rock Platform	Sand Flats	Mud Flats	Salt Marsh	Cliff	Flood Plain[4]	Drainage Basin
1	Glacial valley	Fjord	X					X	X	X			X		X
2		Fjard	0/1/2					X	X	X	X	X		X	X
3	Drowned river valley	Ria	0/1/2					X	X		X	X	X		X
4		Spit enclosed	1/2		X	E/F		X/N		X	X	X	X	X	X
5		Funnel shaped	X		X	E/F		X		X	X	X		X	X
6	Marine/fluvial	Embayment			X		X	X		X	X	X		X	
7	Drowned coastal plain	Tidal inlet	1/2	X	X	E/F		X		X	X	X		X	

Notes:
1 Spits: 0/1/2 refers to number of spits; E/F refers to ebb/flood deltas; N refers to no low water channel; X indicates a significant presence.
2 Linear Banks: considered as alternative form of delta.
3 Channels: refers to presence of ebb/flood channels associated with deltas or an estuary subtidal channel.
4 Flood Plain: refers to presence of accommodation space on estuary hinterland.

2.2 Estuary Classification

In order to test the typology presented in Table 3 a rule base was set-up (Table 4) and applied to data from EMPHASYS, Futurecoast and the JNCC inventory.

This gives results that are reasonably consistent with previous classifications. The main differences arise due to the definition of a rock platform and the role this plays in determining whether an estuary of river origin is a Ria or not. The revised classification also suggests some differences in the distinction between Fjords and Fjards. Also, a number of the coastal bays or shorelines within the Davidson JNCC classification of estuaries are unclassified in this scheme.

The resultant estuary classification for UK estuaries is presented in Table 5. This should be considered as provisional as there remain a number of uncertainties as to the validity of various attributions made in the source data and these are identified by the use of italics. The distinction between Fjords and Fjards also leads to some uncertainty, as already noted.

The classification for UK estuaries presented in Table 5 ensures that the behavioural statements and systems diagrams, presented in the following sections, are applicable to all the estuarine types found in the UK. In doing this, the application of the classification ensures the behavioural relationships explored, developed and applied through the later stages of the project are also applicable and focused on UK.

Table 4. Rules to Identify Estuary Type Using the UK Estuaries Database

Type	Behavioural Type	Rule
1	Fjord	Glacial origin, exposed rock platform set within steep-sided relief and with no significant mud or sand flats
2	Fjard	Glacial origin, low lying relief, with significant area of sand or mud flats
3	Ria	Drowned river valley in origin, with exposed rock platform and no linear banks
4	Spit enclosed	Drowned river valley in origin, with one or more spits and not an embayment
5	Funnel shaped	Drowned river valley in origin, with linear banks or no ebb/flood delta and not an embayment.
6	Embayment	River or marine in origin (i.e. not glacial), with multiple tidal rivers meeting at or near mouth and a bay width/length ratio[1] of 1 or greater, and no exposed rock platform[2]
7	Tidal inlet	Drowned coastal plain in origin, with barrier beaches or spits

Notes:
[1]. Where bay extends from sea opening to the confluence of the rivers
[2]. This condition was only needed to exclude the Plymouth Sound

Table 5. Classification of UK Estuaries Based on Rule Base Defined in Table 4

Id	Estuary name	Behavioural Type		Numeric Type	
		JNCC	EstSim	EstSim	Futurecoast
1	Hayle Estuary	Bar Built Estuary	Spit Enclosed	4	4b
2	Gannel Estuary	Ria	Ria	3	3b
3	Camel Estuary	Ria	Ria	3	3b
4	Taw-Torridge Estuary	Bar Built Estuary	Spit Enclosed	4	4b
5	Blue Anchor Bay	Embayment		0	0
6	Bridgwater Bay	Embayment	Spit Enclosed	4	4c
7	*Severn Estuary*	*Coastal Plain*	*Funnel*	*5*	*3b*
8	Thaw Estuary	Coastal Plain		0	0
9	Ogmore Estuary	Coastal Plain	Spit Enclosed	4	4a
10	Afan Estuary	Bar Built Estuary	Tidal inlet	7	7
11	Neath Estuary	Ria	Spit Enclosed	4	4c
12	Tawe Estuary & Swansea Bay	Embayment	Spit Enclosed	4	4c
13	Loughor Estuary	Coastal Plain	Spit Enclosed	4	4b
14	Carmarthen Bay	Embayment	Embayment	6	4b
15	Milford Haven	Ria	Ria	3	3b
16	Nyfer Estuary	Bar Built Estuary	Ria	3	4c
17	Teifi Estuary	Bar Built Estuary	Ria	3	4c
18	Aberystwyth	Bar Built Estuary	Spit Enclosed	4	3a
19	*Dyfi Estuary*	*Bar Built Estuary*	*Spit Enclosed*	*4*	*3a*
20	Dysynni Estuary	Bar Built Estuary	Spit Enclosed	4	4a
21	*Mawddach Estuary*	*Bar Built Estuary*	*Spit Enclosed*	*4*	*3a*
22	Artro Estuary	Bar Built Estuary	Spit Enclosed	4	7a
23	*Traeth Bach*	*Bar Built Estuary*	*Ria*	*3*	*3a*
24	*Pwllheli Harbour*	*Bar Built Estuary*	*Spit Enclosed*	*4*	*2a*

Id	Estuary name	Behavioural Type		Numeric Type	
		JNCC	EstSim	EstSim	Futurecoast
25	Foryd Bay	Bar Built Estuary	Tidal inlet	7	7b
26	Traeth Melynog	Bar Built Estuary	Tidal inlet	7	7b
27	Cefni Estuary	Bar Built Estuary	Ria	3	3b
28	Alaw Estuary	Fjard Macrotidal	Fjard	2	2b
29	Traeth Dulas	Bar Built Estuary	Ria	3	3a
30	Traeth Coch	Linear shore		0	0
31	Traeth Lavan	Embayment		0	0
32	*Conwy Estuary*	*Coastal Plain*	*Spit Enclosed*	*4*	*3a*
33	Clwyd Estuary	Coastal Plain	Spit Enclosed	4	4b
34	Dee Estuary & North Wirral	Coastal Plain	Spit Enclosed	4	4a
35	Mersey Estuary	*Coastal Plain*	*Ria*	*3*	*3b*
36	Alt Estuary	Coastal Plain	Spit Enclosed	4	0
37	Ribble Estuary	Coastal Plain	Funnel	5	5
38	Morecambe Bay	Embayment	Spit Enclosed	4	4b
39	Duddon Estuary	Coastal Plain	Spit Enclosed	4	4b
40	Esk Estuary (Cumbria)	Bar Built Estuary	Spit Enclosed	4	4b
41	Inner Solway Firth	Complex	Embayment	6	5
42	Rough Firth Auchencairn Bay	Fjard	Fjard	2	0
43	Dee Estuary (Dumfries & Gallo	Fjard	Fjard	2	0
44	Water of Fleet	Fjard	Fjard	2	0
45	Cree Estuary	Fjard	Fjard	2	0
46	Luce Bay	Linear shore	Spit Enclosed	4	0
47	Garnock Estuary	Bar Built Estuary	Spit Enclosed	4	0
48	Hunterston Sands	Linear shore		0	0
49	Clyde Estuary	Fjord	Fjard	2	0
50	Ruel Estuary	Fjord	Fjord	1	0
51	Loch Gilp	Fjord	Fjord	1	0
52	Tr_igh Cill-a-Rubha	Embayment	Fjard	2	0
53	Loch Gruinart	Fjard	Fjard	2	0
54	Loch Crinan	Fjard	Fjard	2	0
55	Kentra Bay	Fjard	Fjard	2	0
56	Loch Moidart	Fjard	Fjord	1	0
57	Tr_igh Mh¢r	Embayment		0	0
58	Bagh Nam Faoilean	Fjard	Fjard	2	0
59	Oitir Mh¢r	Fjard	Fjard	2	0
60	Tr_igh Vallay	Fjard	Fjard	2	0
61	Oronsay	Fjard	Fjard	2	0
62	Scarista	Embayment	Fjard	2	0
63	Tr_igh Luskentyre	Fjord		0	0
64	Camus Uig	Fjard	Fjard	2	0
65	Laxdale Estuary	Fjard	Fjard	2	0
66	Kyle of Durness	Fjard	Fjard	2	0
67	Kyle of Tongue	Fjard	Fjard	2	0

Id	Estuary name	Behavioural Type		Numeric Type	
		JNCC	EstSim	EstSim	Futurecoast
68	Torrisdale Bay	Fjard	Fjard	2	0
69	Melvich Bay	Fjard	Fjard	2	0
70	Otters Wick	Fjard	Fjard	2	0
71	Cata Sand	Bar Built Estuary	Tidal inlet	7	0
72	Kettletoft Bay	Fjard	Tidal inlet	7	0
73	Deer Sound and Peter's Pool	Fjard	Fjard	2	0
74	Loch Fleet	Bar Built Estuary	Spit Enclosed	4	0
75	Dornoch Firth	Complex	Ria	3	0
76	Cromarty Firth	Complex	Fjard	2	0
77	Inner Moray Firth	Complex	Ria	3	0
78	Lossie Estuary	Bar Built Estuary	Spit Enclosed	4	0
79	Spey Bay	Bar Built Estuary	Spit Enclosed	4	0
80	Banff Bay	Embayment	Ria	3	0
81	Ythan Estuary	Bar Built Estuary	Spit Enclosed	4	0
82	Don Estuary	Coastal Plain	Spit Enclosed	4	0
83	Dee Estuary (Grampian)	Coastal Plain	Ria	3	0
84	St Cyrus	Bar Built Estuary	Spit Enclosed	4	0
85	Montrose Basin	Bar Built Estuary	Spit Enclosed	4	0
86	Firth of Tay	Complex	Spit Enclosed	4	0
87	Eden Estuary	Bar Built Estuary	Spit Enclosed	4	0
88	Firth of Forth	Complex	Ria	3	0
89	Tyninghame Bay	Bar Built Estuary	Spit Enclosed	4	0
90	Tweed Estuary	Complex	Ria	3	3b
91	Lindisfarne & Budle Bay	Barrier Beach	Tidal inlet	7	0
92	Alnmouth	Bar Built Estuary	Spit Enclosed	4	4b
93	Warkworth Harbour	Bar Built Estuary	Spit Enclosed	4	4a
94	Wansbeck Estuary	Coastal Plain	Spit Enclosed	4	4a
95	Blyth Estuary (Northumberland)	Bar Built Estuary	Ria	3	4a
96	*Tyne Estuary*	*Complex*	*Ria*	*3*	*3b*
97	Wear Estuary	*Complex*	*Ria*	*3*	*3a*
98	Tees Estuary	Coastal Plain	Spit Enclosed	4	4b
99	Esk Estuary (Yorkshire)	Complex	Ria	3	3b
100	Humber Estuary	Coastal Plain	Spit Enclosed	4	4a
101	The Wash	Embayment	Embayment	6	6
102	North Norfolk Coast	Barrier Beach	Tidal inlet	7	0
103	Breydon Water	Bar Built Estuary	Spit Enclosed	4	4a
104	Oulton Broad	Bar Built Estuary	Spit Enclosed	4	4a
105	Blyth Estuary (Suffolk)	Bar Built Estuary	Spit Enclosed	4	4a
106	Ore-Alde-Butley	Bar Built Estuary	Spit Enclosed	4	4a
107	Deben Estuary	Coastal Plain	Spit Enclosed	4	4b
108	Orwell Estuary	Coastal Plain	Spit Enclosed	4	4a
109	Stour Estuary	Coastal Plain	Spit Enclosed	4	0
110	Hamford Water	Embayment	Tidal inlet	7	4b

Id	Estuary name	Behavioural Type		Numeric Type	
		JNCC	**EstSim**	**EstSim**	**Futurecoast**
111	Colne Estuary	Coastal Plain	Spit Enclosed	4	4b
112	Blackwater Estuary	Coastal Plain	Spit Enclosed	4	4a
113	Dengie Flat	Linear shore		0	0
114	Crouch-Roach Estuary	Coastal Plain	Spit Enclosed	4	4a
115	Maplin Sands	Linear shore		0	0
116	Southend-on-Sea	Linear shore	Spit Enclosed	4	0
117	Thames Estuary	Coastal Plain	Funnel	5	5
118	South Thames Marshes	Linear shore		0	0
119	Medway Estuary	Coastal Plain	Spit Enclosed	4	4a
120	Swale Estuary	Coastal Plain	Spit Enclosed	4	4a
121	Pegwell Bay	Embayment	Spit Enclosed	4	4a
122	Rother Estuary	Bar Built Estuary	Spit Enclosed	4	4b/4c
123	*Cuckmere Estuary*	*Coastal Plain*	*Spit Enclosed*	*4*	*4c*
124	*Ouse Estuary*	*Coastal Plain*	*Spit Enclosed*	*4*	*4a*
125	Adur Estuary	Coastal Plain	Spit Enclosed	4	4a
126	Arun Estuary	Coastal Plain	Spit Enclosed	4	4a
127	Pagham Harbour	Bar Built Estuary	Tidal inlet	7	7a
128	Chichester Harbour	Bar Built Estuary	Tidal inlet	7	7a
129	Langstone Harbour	Bar Built Estuary	Tidal inlet	7	7a
130	Portsmouth Harbour	Bar Built Estuary	Tidal inlet	7	7a
131	Southampton Water	Coastal Plain	Spit Enclosed	4	4a
132	Beaulieu River	Bar Built Estuary	Spit Enclosed	4	4a
133	Lymington Estuary	Coastal Plain	Spit Enclosed	4	4c
134	Bembridge Harbour	Coastal Plain	Spit Enclosed	4	4b
135	Wootton Creek & Ryde Sands	Coastal Plain	Spit Enclosed	4	4c
136	*Medina Estuary*	*Coastal Plain*	*Funnel*	*5*	*3b*
137	Newtown Estuary	Bar Built Estuary	Spit Enclosed	4	4c
138	Yar Estuary	Coastal Plain	Spit Enclosed	4	4c
139	Christchurch Harbour	Bar Built Estuary	Spit Enclosed	4	3a
140	Poole Harbour	Bar Built Estuary	Spit Enclosed	4	4b
141	The Fleet & Portland Harbour	Bar Built Estuary	Tidal inlet	7	4a
142	Axe Estuary	Bar Built Estuary	Spit Enclosed	4	4c
143	Otter Estuary	Bar Built Estuary	Spit Enclosed	4	4c
144	Exe Estuary	Bar Built Estuary	Spit Enclosed	4	4a
145	Teign Estuary	Ria	Spit Enclosed	4	4a
146	Dart Estuary	Ria	Ria	3	3b
147	Salcombe & Kingsbridge Estuary	Ria	Ria	3	3b
148	Avon Estuary	Ria	Ria	3	3b
149	Erme Estuary	Ria	Ria	3	3b
150	Yealm Estuary	Ria	Ria	3	3b
151	Plymouth Sound	Ria	Ria	3	3b
152	Looe Estuary	Ria	Ria	3	3b
153	Fowey Estuary	Ria	Ria	3	3b

Id	Estuary name	Behavioural Type		Numeric Type	
		JNCC	**EstSim**	**EstSim**	**Futurecoast**
154	Falmouth	Ria	Ria	3	3b
155	Helford Estuary	Ria	Ria	3	3b
156	*Lough Foyle*	*Coastal Plain*	*Fjard*	*2*	*0*
157	*Bann Estuary*	*Bar Built Estuary*	*Spit Enclosed*	*4*	*0*
158	*Larne Lough*	*Coastal Plain*	*Fjard*	*2*	*0*
159	*Belfast Lough*	*Coastal Plain*	*Fjard*	*2*	*0*
160	*Strangford Lough*	*Complex*	*Fjard*	*2*	*0*
161	*Killough Harbour*	*Embayment*	*Ria*	*3*	*0*
162	Dundrum Bay	Bar Built Estuary	Tidal inlet	7	0
163	*Carlingford Lough*	*Complex*	*Fjard*	*2*	*0*

Notes:

[1] The JNCC dataset includes Linear Shores. For completeness, the rule base presented in Table 4 has been applied to the whole dataset and as a result Linear Shores are also included in Table 5. However, these forms are not carried through into other tasks within the project.

[2] For each estuary, the classification derived within the JNCC work and within Futurecoast is presented for comparative purposes. Alongside these data, the classification derived within this project through the application of the rule base presented in Table 4 is presented (labelled EstSim) in the form of the Behavioural Type and Numeric Type. It is this classification that is carried through to the remainder of the project.

3. REVIEW OF SYSTEMS APPROACH

This Task is concerned with the review of the systems approach and will provide the background understanding for developing systems diagrams of estuaries and the relevant geomorphological elements.

The systems diagrams and behavioural descriptions (for estuaries and geomorphological elements together form the core of information required to explore translation of the estuary 'system' into formalisation (Objective 4) and Simulation (Objective 5).

3.1 What is a Systems Approach?

The systems based approach involves separating out sub-systems and their interactions in order to understand the system organisation and define its behaviour. It thus combines the physical elements and the dynamics of the interactions between those elements in an effort to explain how the different elements that make up the system interact and respond to change (Cowell & Thom, 1994; Capobianco, *et al*. 1999).

The systems approach has been applied and reviewed by various workers (Chorley & Kennedy, 1971; White *et al*., 1984; Cowell & Thom, 1994; Capobianco *et al*., 1999 and Townend 2003) and some of the key issues identified from these studies are summarised here.

3.2 Systems Diagrams Overview and Examples

Systems diagrams provide a means of capturing the key attributes of a system by identifying the system elements and their interactions. A system diagram is a flowchart representation and its ability to capture the systems behaviour will depend upon the fundamental knowledge of coastal processes and the ways in which these are expressed. Different examples of system diagrams that demonstrate a number of key features are presented in Figures 2-5.

It is important to note that in the examples provided in Figures 2-5, the systems diagrams are attempting to identify the presence of, and interactions between, the key elements within natural systems. The systems diagrams do not include any anthropogenic influences on these systems.

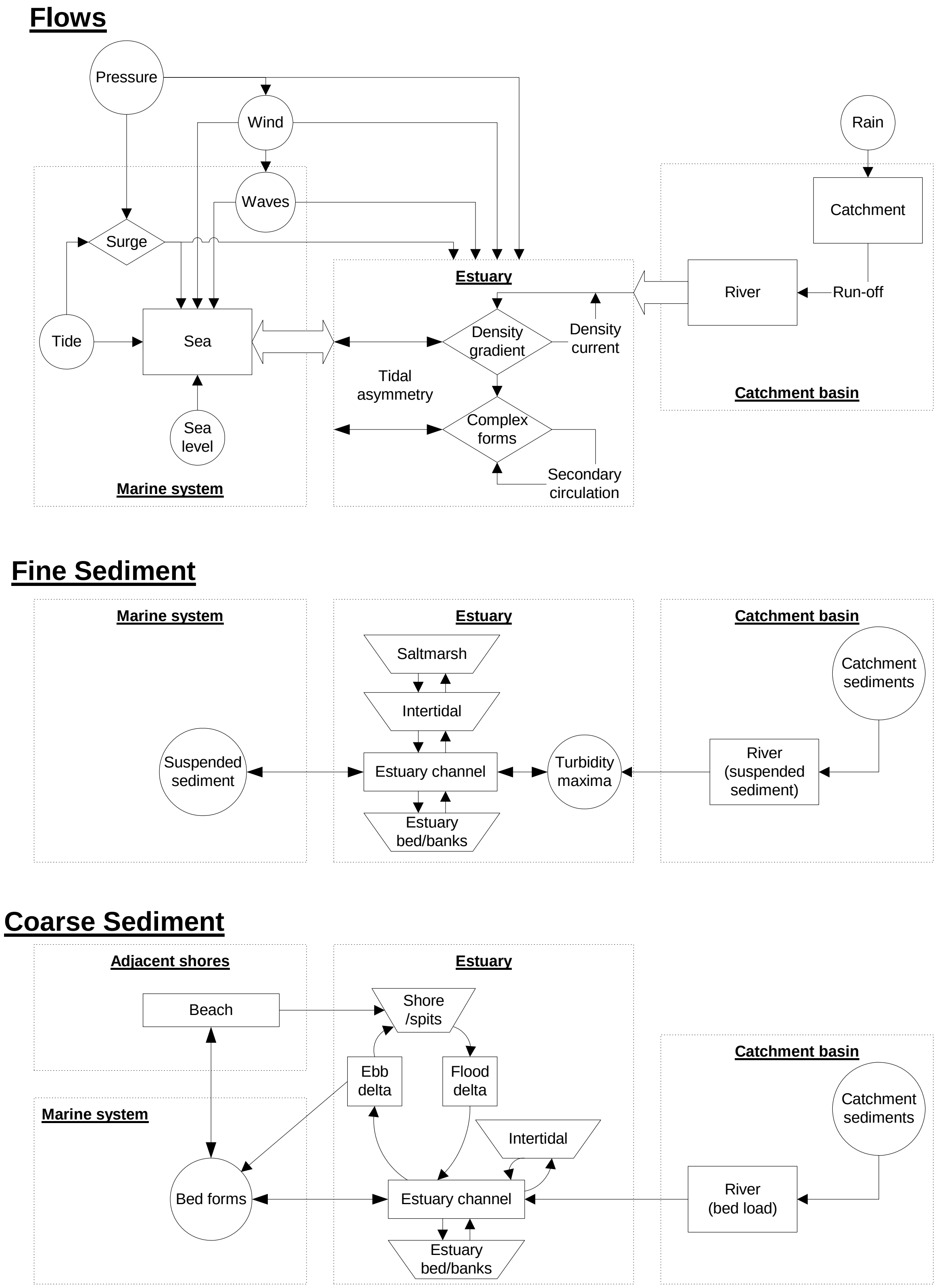


Figure 2. **Estuary represented as flows, fine and coarse sediment interactions (Townend, 2003)**

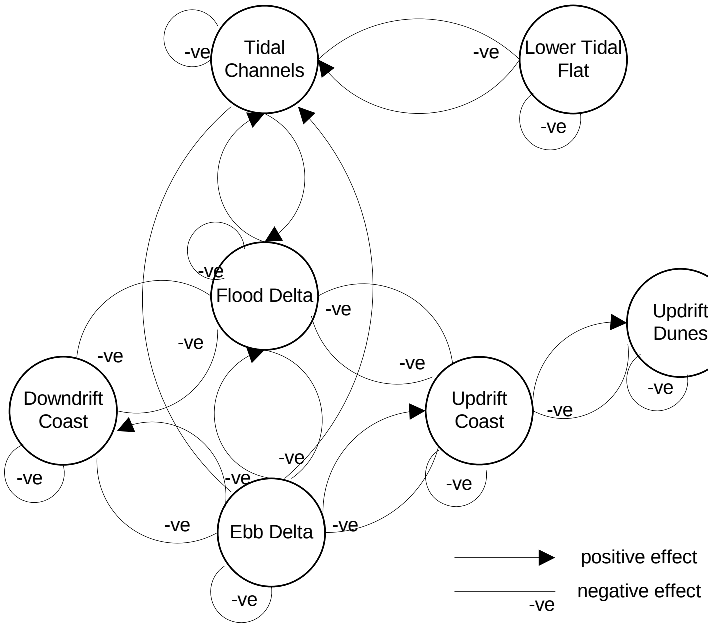


Figure 3. Signed graph representation for the impacts of sea-level rise on an inlet or lagoon entrance (Capobianco *et al.*, 1999)

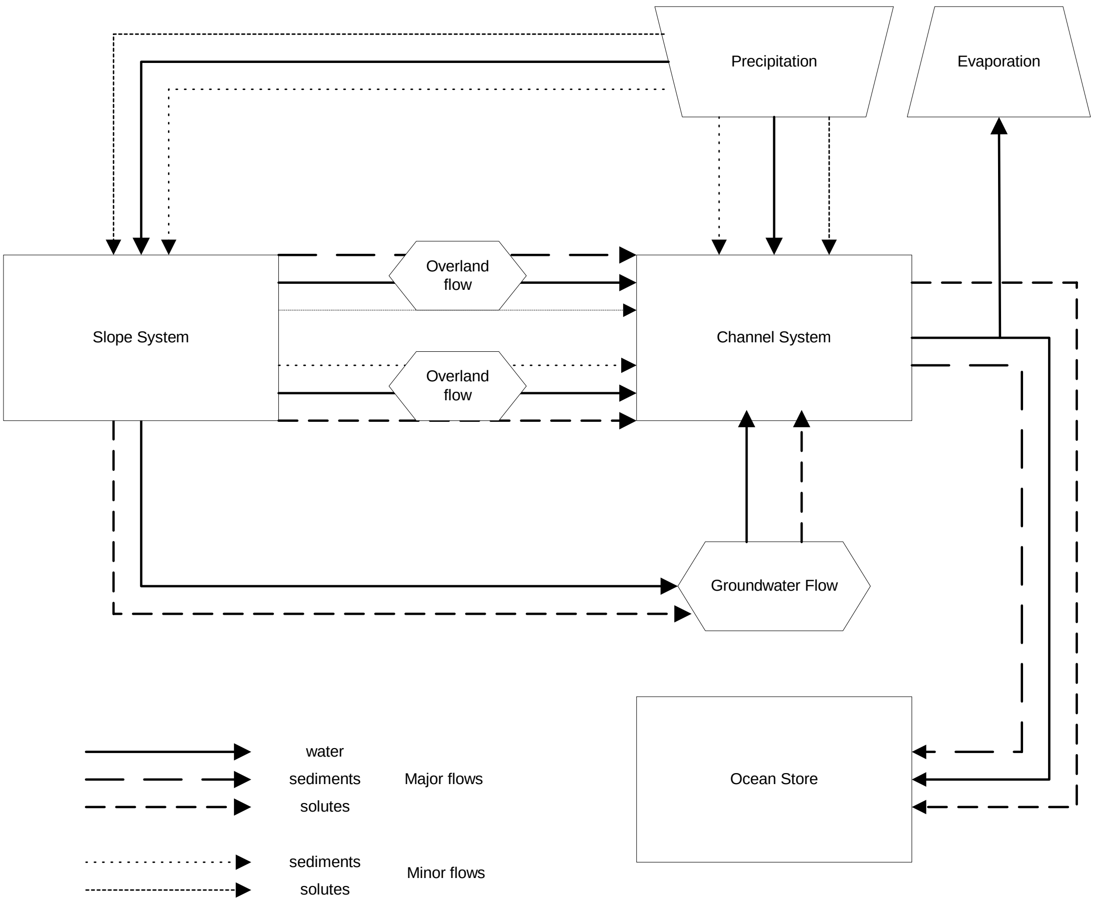
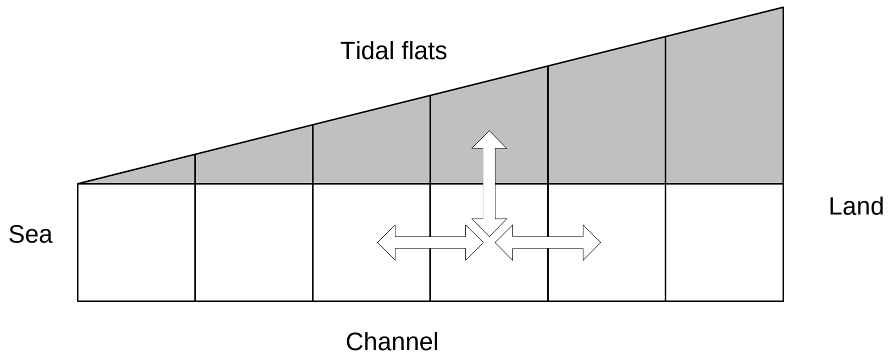
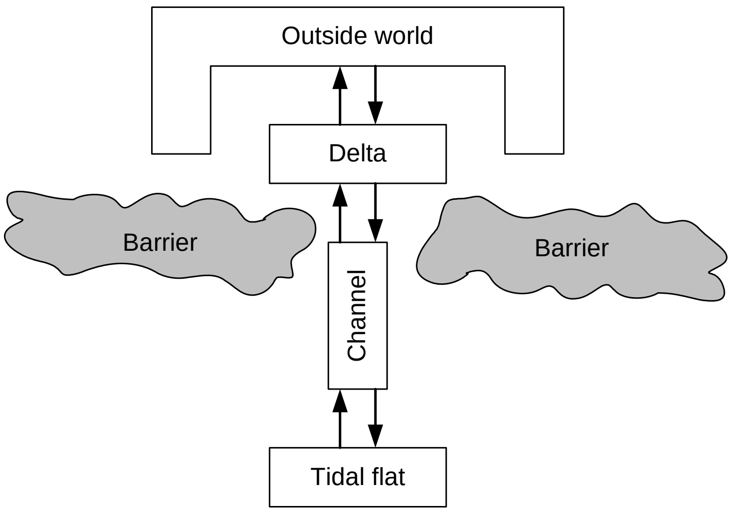


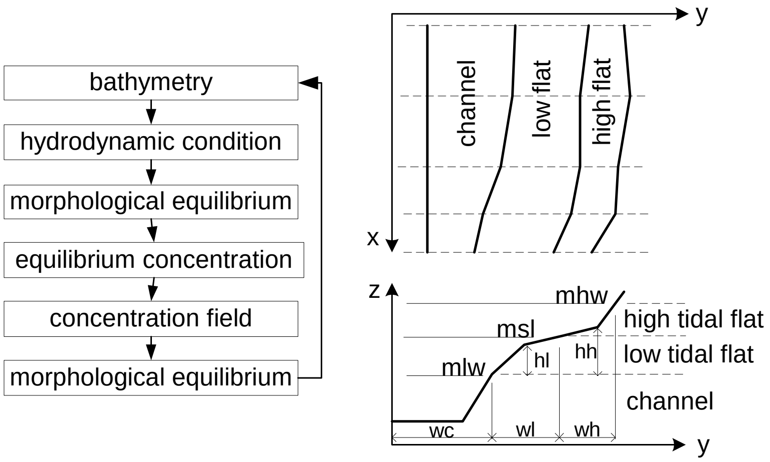
Figure 4. Diagram showing the pathways through the catchment basin system (White *et al.*, 1984)



a) Tidal basin schematisation used by van Dongeren and de Vriend (1994)



b) Schematisation of elements and exchanges within the ASMITA model



c) Procedure and schematisation used in ESTMORF (Wang et al, 1998)

Figure 5. Schematisations used in selected tidal inlet models

3.3 Abstraction and System Levels

The complexity of the coastal system, range of physical processes present and relevant spatial and temporal scales will determine the how the system is represented.

If every known system element and interaction were presented on one system diagram the complexity would inhibit an understanding of the whole system. Hence, abstraction is an important procedure for separating the system into layers.

Figure 2 demonstrates abstraction of different processes involving different mediums (water, and coarse/fine sediments) into three separate layers operating over the same timescale.

Abstraction must also be considered over the hierarchy of spatial and temporal scales (Figure 6). One of the driving aims behind this research is to inform decision making concerning coastal management issues over the medium-term (decadal period) where uncertainties in current modelling approaches limit the accuracy of solutions.

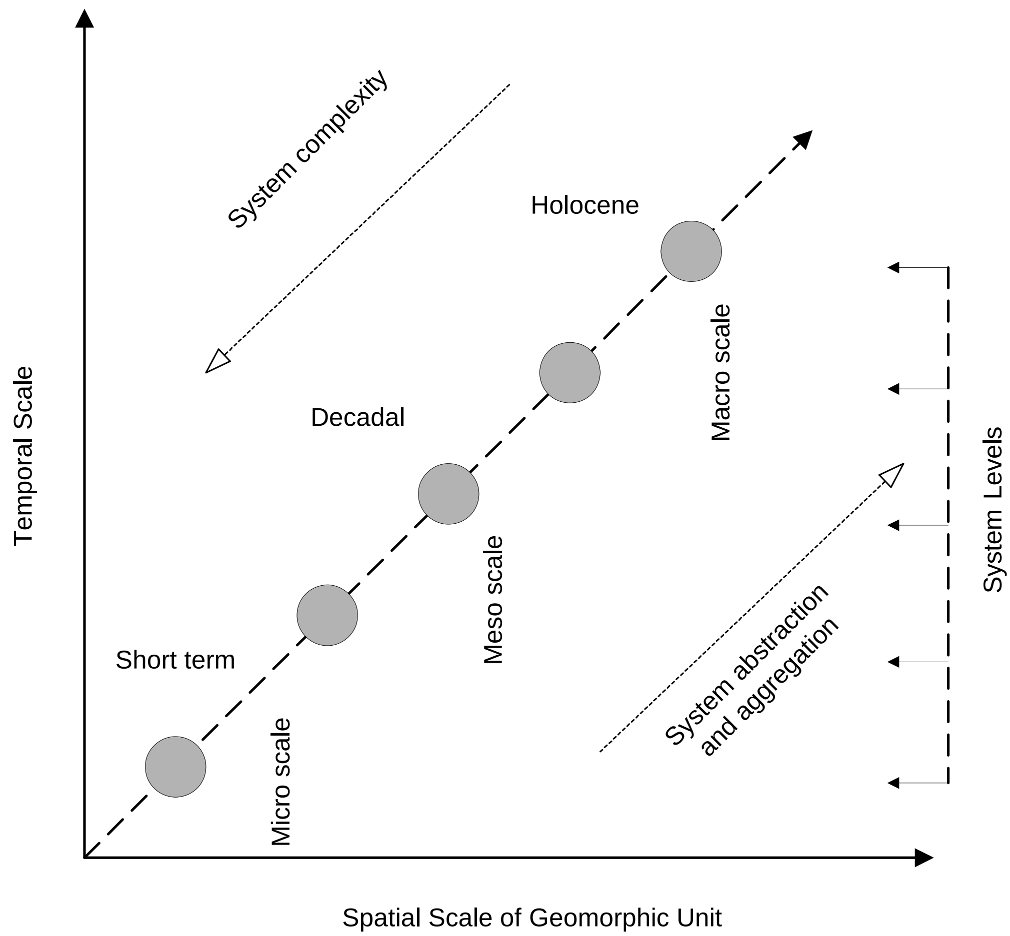


Figure 6. General relationship between temporal and spatial scales of geomorphic evolution showing different levels of system abstraction

For coastal geomorphology various levels of abstraction have been cited and categorised (Townend, 2003; Cowell *et al*., 2004).

One possible categorisation is as follows:

- Macro scale - regional land mass behaviour.
- Meso scale - geomorphological unit behaviour.
- Micro scale - geomorphological features.
- Nano scale - particle behaviour.
- Atto scale - sub-atomic/quantum behaviour.

Each level of abstraction could be defined as a behaviour model (Section 3.6), which can be chosen on the basis of the type of question we are seeking to answer.

At any one level of synthesis, elements and interactions that add detail and complexity but make only a minor contribution to system response can be omitted. This is an explicit process when abstracting from a high level of detail to subsequent lower levels but is also an important property of qualitative/behavioural modelling (aggregation) where the behavioural description of system interactions does not need to be based on the underlying physical processes (Section 3.6). Essentially, it follows that the detailed system/processes that dominate the level of interest will be taking place at the next level down. Therefore each level is doing some form of averaging to relate the detailed structure at one level to the more general behaviour at the next level (Schumm & Lichty, 1965).

An example of a top-level abstraction of an estuary system, shown as a simple tidal inlet, is given by the ASMITA model (Figure 5b). Here, sub-systems could be added to provide the detail of subsequent lower levels.

However, abstraction should be treated with care to ensure that relatively small exchanges at any one level are not ignored at a higher level purely on the basis of their scale since the accumulation of these small exchanges may actually produce morphologically significant effects (Cowell *et al*., 2004).

In determining the rationale for system abstraction for each level, there does not seem to be an obvious choice. Each level may comprise elements that interact over the same temporal or spatial scales or may be more complex as noted above. Cowell *et al*., (2004) suggest the 'cascade' of levels is partitioned on the basis that each level forms an internally sediment-sharing system.

3.4 Estuary Context

The dynamical nature of estuaries provides a potentially complex regime for developing a systems approach. To provide the longer term context, the contemporary form of an estuary was assumed during the rise of relative sea-level following the last glacial maximum. The submerged or inherited form plays a role in dictating the composition of the estuary system in terms of geomorphic elements and also exerts an influence on how the system behaves in more contemporary terms by influencing, for example the interaction of the elements via sediment exchanges. On these contemporary timescales, both the landward catchment and marine setting influence estuaries with sediment transport providing the coupling mechanism between form and hydrodynamics (feedback mechanism). Variations in energy distributions between and within different estuary types together with the available sediment composition (fine and coarse grades) controls the range of morphological forms present. If the boundary conditions remained constant we might expect a steady state equilibrium to establish itself. Whilst it is conjectured that some estuaries may be close to such a condition, in most cases the continuous variation of the controls, such as relative sea-level, fresh water and sediment supply, mean that the system is usually closer to a dynamic equilibrium.

Given the above basic description, it can be seen that there will be a range of physical components to be defined within an estuary as part of a systems approach. Different components that may be categorised are shown in Table 6.

Table 6. Physical Components Mapped Within Systems Approach

Physical Component	Nature	Examples
Geomorphic forms[1]	Sources, stores and sinks of sediment that also act as boundary conditions that can alter fluid flows.	Spit, Barrier beach, Dune, Delta, Rock platform, Ebb and flood channels, Sandflat, Mudflat, Saltmarsh, Cliff (or bluff), Drainage basin.
Forcing factors/ Inputs and Outputs	Environmental conditions that form boundary conditions (inputs/outputs) and drive the physical processes within the system.	Wind, pressure, tides, wind waves, surges, river flow, suspended sediment, bedload sediment, tidal discharge and energy, precipitation.
Transport/Flows	Provides link between Geomorphic forms and Forcing factors and identified a flow of matter/energy, identifying the direction of influence.	Energy, bedload sediment, suspended sediment, water.
Processes/ Relationship	Physical processes (typically internal) that provide the mechanism for interaction between geomorphic forms. (May be defined as the 'relationship/response' within a behaviour model).	Salinity gradient, residual circulation, density currents, tidal asymmetry, tidal pumping, refraction, shoaling, diffraction, wave-current interaction, littoral drift, turbidity maximum, erosion, deposition, consolidation, tidal range.

[1] The range of geomorphic forms shown were defined in part during the conceptualisation workshop to this project (Scientific Objective 1).

3.5 System Diagram Convention

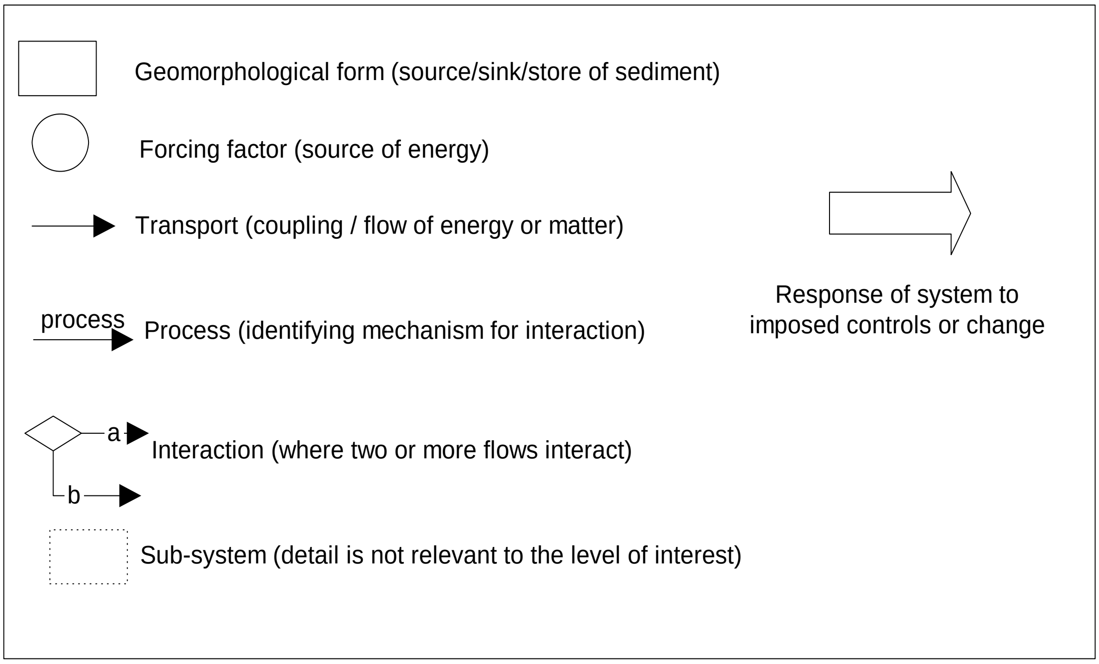
The objective of defining systems diagrams is to represent the interactions between system components. This should ideally capture of the behavioural attributes of the system and inform abstraction and aggregation to different system levels.

The physical components given in Table 6 can be simply identified within a systems diagram by different symbols/nomenclatures (Figure 7) after adapting the convention used by Wilson (1982).

In order to better express system interactions, the above convention can be extended where the relationships between different system elements are known. For instance, the example given in Figure 3 shows how an interaction or coupling flow can be defined in terms of the nature of response of element. In this case the response can be for a positive or negative tendency/effect.

The relative dominance of interactions and flows is shown on Figure 4 where minor and major flows are differentiated by the ***boldness*** of the connector. This system also differentiates between the transport of different mediums on the same system level by using a range of ***line types or colours***.

Use of the above convention is not meant to constrain systems representation. Alternative techniques should be applied where these can convey the desired system behaviour or response.



Note: The nature of the geomorphological form in terms of its role as a source/store and/or sink will implicitly be given by the presence/absence of a connecting flow and the direction of transport.

Figure 7. System diagram symbol convention

3.6 Behaviour Modelling

The discussion in previous Sections has focused on the role of the systems approach and systems diagrams to map out interactions within an estuarine system. This approach can map the system components (elements and interactions) at a specified level of interest. However, attempting to model this detailed system is limited by current understanding of the detailed processes and is one of the reasons why a behavioural systems approach as an alternative to process modelling is being investigated.

The limitation within the systems diagram approach is fully recognised (Townend, 2003). It is noted that that whilst systems diagrams make clear the nature of flows of energy and matter, and the interactions and feedbacks between elements, they say little about the relationship between components and the character of any response.

This is where *behavioural* or *qualitative* modelling (Capobianco *et al*., 1999) can be thought of as extending the basic systems approach. The concept of behavioural modelling is to develop an understanding of the behaviour of the system by capturing the nature of relationships between system components and mapping it onto a simple model, which exhibits the same behaviour, but which does not need to have any relationship to the underlying physical processes. Whereas systems diagrams highlight the presence of interactions, the behavioural approach places emphasis on developing the interaction as a relationship (response). The difference between the two approaches is evident on Figure 3, which both identifies interactions and provides a behavioural response. In the context of an estuarine system the identification of a behavioural system is an attempt to integrate geomorphological units that are spatially contiguous into a unified entity that reflects how it is likely to change.

A behavioural system representation of the coast is therefore essentially a top down view as it seeks to capture an overall coastal response. However it can be seen that arriving at such a system view could be developed in a number of ways such as from either a bottom up 'reductionist' starting point with a gradual increase in abstraction and aggregation, or directly from the top after understanding a form of coastal response that can be captured by a behavioural relationship.

3.7 Behavioural Relationships

In the context of this project, mapping of estuarine system components (systems diagrams) can be considered as the first stage in developing behavioural models. To develop a behavioural model, interactions within the systems approach will need to be represented not simply by directionality, but also in the form of a relationship or response.

These responses may take a variety of forms, including quantitative and qualitative descriptions, such as:

- Simplified numerical model
- Parameterisations (derived from detailed modelling)
- Geometric rules (that define the target shape in response to change)
- Morphological concepts (that define large scale response to change, such as rollover or tidal asymmetry)
- Algorithms (underlying physical basis for hydrodynamic and sediment transport processes)
- Decision rules (derived from variety of sources such as detailed modelling and experience/knowledge)
- Feedback (positive and negative leading respectively to growth and dampening)

In the case of qualitative relationships a set of operations will need to be defined in order to propagate effects through the model domain.

Given a system composed of a number of abstracted levels, there seems no reason why the behavioural response at each level could not be defined using alternative techniques.

3.8 Next Step

The discussion in previous Sections provides supporting information for developing the systems based approach for estuary systems within this research theme. The development of system diagrams for the range of geomorphological forms shown in Table 3, together with the supporting behavioural statements is therefore an important precursor to developing behavioural models through mathematical formalisation and system simulation tools (Scientific Objectives 4 and 5).

4. PROTOCOL

4.1 Introduction

In Section 2 an estuary typology was developed based upon the presence/absence of component geomorphological elements. This typology was able to classify seven generic estuary types and was tested using the Estuaries Database to classify estuaries within the UK.

The following Section builds on the earlier work in Section 2 and the review of the systems based approach in Section 3 to provide a simple protocol for application to present statements of the seven different estuary types and eleven component geomorphic elements (Section 5 and Appendices A-K respectively).

The presentation of behavioural statements comprises two stages, including both a behavioural (textural) description and systems diagrams.

4.2 Protocol for Behavioural Descriptions

The purpose of developing behavioural statements is to facilitate (i) our understanding of relationships between different elements and the key forcing factors and (ii) the translation of these relationships into a model domain capable of simulation.

The textural description for each estuary type is at a high level identifying the main behavioural attributes, whilst for each geomorphic element the following sub headings provide a guide to the descriptive content required:

- **Definition of Geomorphic Element (GE):**
  Providing an overall definition of the GE in question through for example, a description of the key aspects of the form, formation, processes or location within an estuary system.

- **Function:**
  Defining the role of the GE within the physical system in terms of exchanges of energy and mass.

- **Formation and Evolution:**
  Providing details of the processes that lead to the formation of the particular GE and how the GE develops and evolves over time.

- **General Form:**
  Describing the characteristic shape (or component shapes) of the GE, where appropriate highlighting the prevailing conditions under which a particular form will be adopted.

- **General Behaviour:**
  The general behaviour of the GE is described in terms of how the GE may respond to the varying forcing to which it can be exposed.

- **Forcing Factors:**
  This section describes the key processes (for example, wave attack) responsible for shaping the GE, with details provided where appropriate of role of the forcing processes.

- **Evolutionary Constraints:**
  This section details the factors that may alter or constrain the development of the GE leading to a differing evolution due to that constraint.

- **Behavioural Timescales:**
  As discussed above, landforms will respond to forcing over a range of time and space scales, and will exhibit characteristic responses of differing scales. For each GE's the behaviour of the element is discussed over the three timescales (as defined in Section 4.5 below).

- **Interactions with Other Geomorphic Elements:**
  Each GE will be linked to other GE's present within a particular estuary system. This section identifies the interactions in terms of flows of energy and/or matter between GE's. Interactions are identified and discussed either in terms of general interactions (for both elements within the estuary system and external to the estuary system) or interaction with specific geomorphic elements.

4.3 Literature Sources

In addition to the input from knowledge and methods presented within the Futurecoast project and the scientific literature, completion of the geomorphological descriptions was aided by improved knowledge from the EstProc project (EstProc, 2004).

4.4 Protocol for Systems Diagrams

A mapping of the estuary system in terms of key geomorphological elements within the coastal and river basin setting is shown in Figure 8 and a more detailed representation of the generic estuary elements shown in Figure 9. Using this generic figure (Figure 9) as a basis system diagrams have been prepared for each estuary type (Section 5: Figures 11-17) this helped to highlight the differences between types and to identify the classification rule base (Section 2).

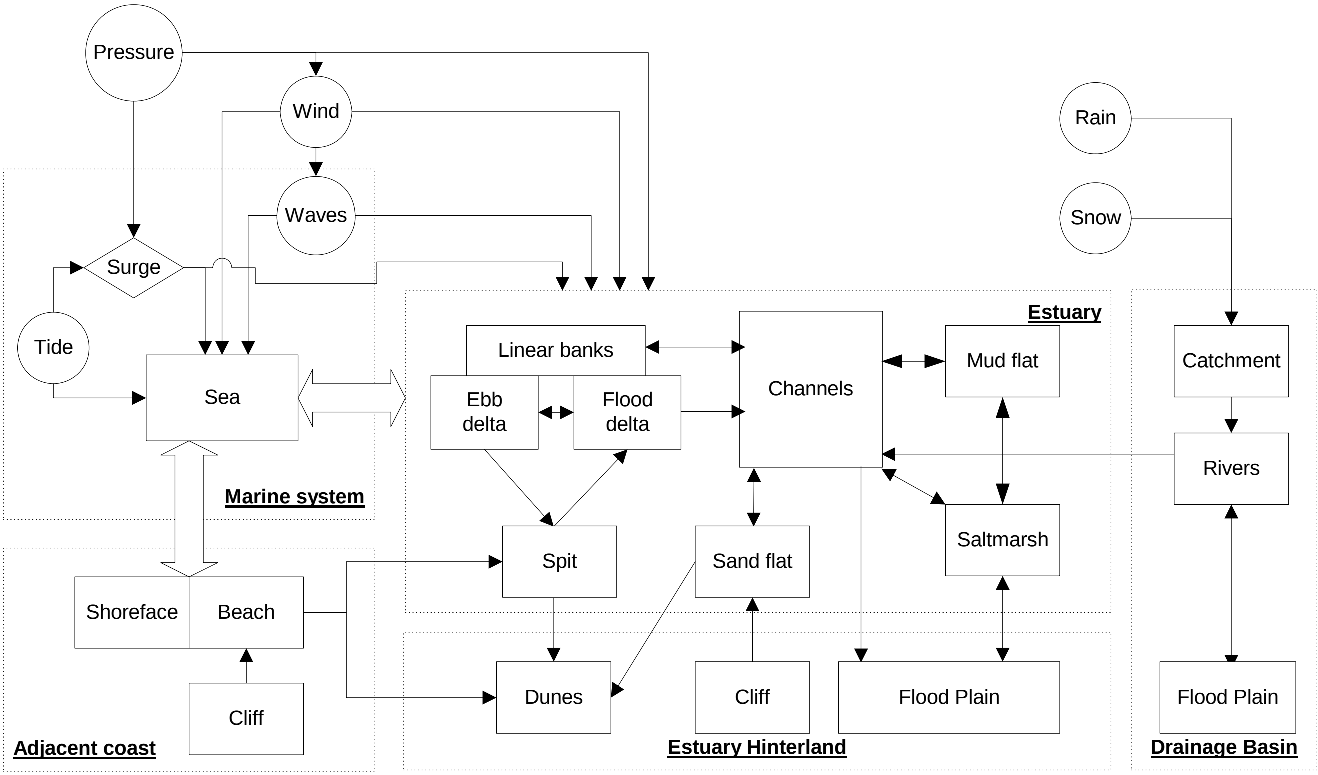


Figure 8. Simplified estuary within coastal and catchment setting

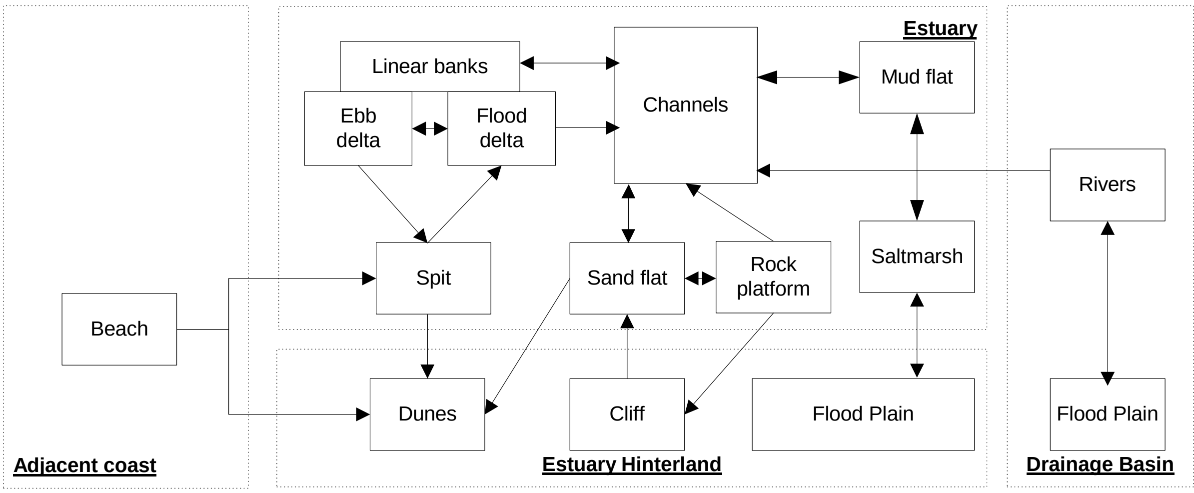
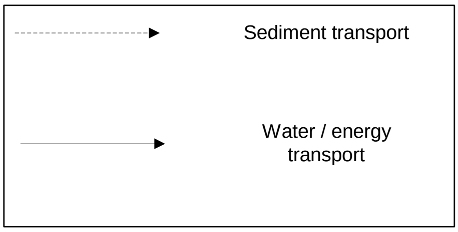


Figure 9. Generic estuary geomorphological units

Notes:
- (i) Holocene bed is not shown, but will be present as a consequence of long-term accretion and consolidation.
- (ii) Channels can include both ebb/flood channels and/or a subtidal channel.
- (iii) Sand flats include mixed sediment beds.
- (iv) Linear banks and the ebb/flood delta are alternatives (usually reflecting the tidal range).
- (v) Flood plains are differentiated between those in the upstream drainage basin and those adjacent to the estuary, although they may represent a continuum.

Systems diagrams for both estuary type and geomorphic elements have applied the general convention shown in Section 3.5 for describing the nature of the interactions.

The connections between elements and their sub-system components in the short-medium term representation is defined as either a dashed line indicating sediment transport or a full line indicating an input of water or energy without sediment.



The medium-long term representation requires a slightly different approach and here, each system diagram has been set out in an attempt to show the main controls on morphological form and development and the subsequent response of the system.

4.5 Temporal and Spatial Scales

The topic of temporal and spatial scales within a systems approach and levels of systems abstraction is discussed in Section 3.3. Morphological behaviour will depend on, amongst other factors, the temporal and spatial scale of consideration, or the level of abstraction. Defining an appropriate level of abstraction for the behavioural statements is therefore key in capturing the key aspects of estuarine systems behaviour.

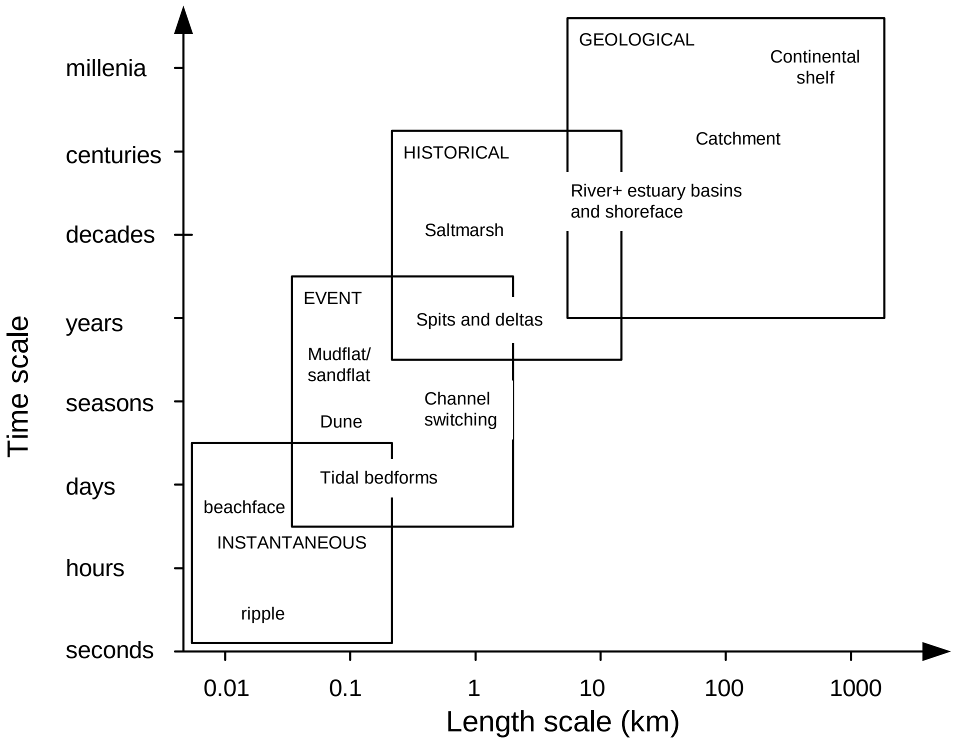


Figure 10. Temporal and spatial scales of behavioural responses (After: Cowell & Thorn, 1994)

Different processes will dominate different elements of the system over different timescales. This is clearly demonstrated by Figure 10, illustrating the different behavioural timescales for different system components.

The spatial scales for the production of behavioural statements within this report have been defined, i.e. at estuary wide level (estuary type statements) and geomorphic element level.

In terms of temporal scales, for the purpose of describing geomorphic systems within this report the emphasis is on the ***response*** of the systems to forcing factors and interactions with other elements, and three timescales have been chosen as an initial guide:

- Short Term (responses within a year);
- Medium-term (responses over decadal to century scale changes);
- Long-term (Responses over decadal to Holocene timescales, i.e. up to the last 10,000 years).

The short-term period can be thought of as how the system responds to ***maintain*** its form through interactions with other elements. Actions dominating this response duration will typically be continuous tidal and wave processes taking account of seasonal variability. Behavioural responses over the medium term will be dominated by intermittent or episodic forcing, such as storms, while in the longer term, morphological responses are likely to be dominated by forcing such as relative sea-level change or tectonics.

4.6 Application of Protocol

The above protocol for the development of the descriptive (textural) and diagrammatic components of the behavioural statement have been applied at two generic levels of system abstraction:

1. Estuary type statements: high level descriptions of each of the seven estuary behavioural types including identification of the component geomorphic elements, using a systems diagram based on the convention shown on Figure 9. These descriptions relate to specifically to UK estuaries as this is the focus of the project. It should be noted that the properties of the different behavioural types are likely to vary in different areas of the world. These are presented in Section 5.

2. Geomorphic Element Statements: Textural descriptions for each of the eleven geomorphic elements, based on the structure presented in Section 4.2. Each geomorphic element is represented by a systems diagram which covers the short - medium term and medium to long term. These are provided in Appendices A-K.

At this stage of the project the intention is to capture, in a qualitative sense, the components and linkages at different levels within the estuary system in order that these definitions may be formalised at the next phase of the project. At this stage therefore, the definition provided in the behavioural statements, at the two generic levels above, is for ‘natural systems’ and as such the statements do not account for anthropogenic effects or indeed the behaviour and responses that may result from anthropogenic influences within the systems that are being defined.

In addition to developing behavioural statements on a generic basis, two specific case study examples have also been produced through application of the protocol to two UK estuaries, namely the Humber and Southampton Water. These two case studies are presented and discussed further in Section 6.

5. ESTUARY TYPE DESCRIPTIONS

This Section provides a brief textural description and generic system diagram of each of the estuarine behavioural types as identified in Section 2. The geomorphological units present within each different estuary type are highlighted on each system diagram.

5.1 Estuarine Behavioural Type 1: Fjord

Fjords are generally long, deep and narrow features that are bounded by relatively erosion-resistant, steeply rising slopes. They are formed by the submergence of glacially over deepened valleys (known as troughs) due to a rising relative sea-level after the melting of the Pleistocene ice sheets. Fjords extend to great depths along most of their length, even close to their head, but tend to shallower depths close to their mouths to form a sill in solid rock. They generally have only small but highly seasonally variable river flow, often with tributary streams entering the system as waterfalls from hanging valleys. Only a small number of fjords exist in the UK, confined mainly to highland regions in Scotland. One of the best UK examples of a fjord is Loch Etive in Western Scotland.

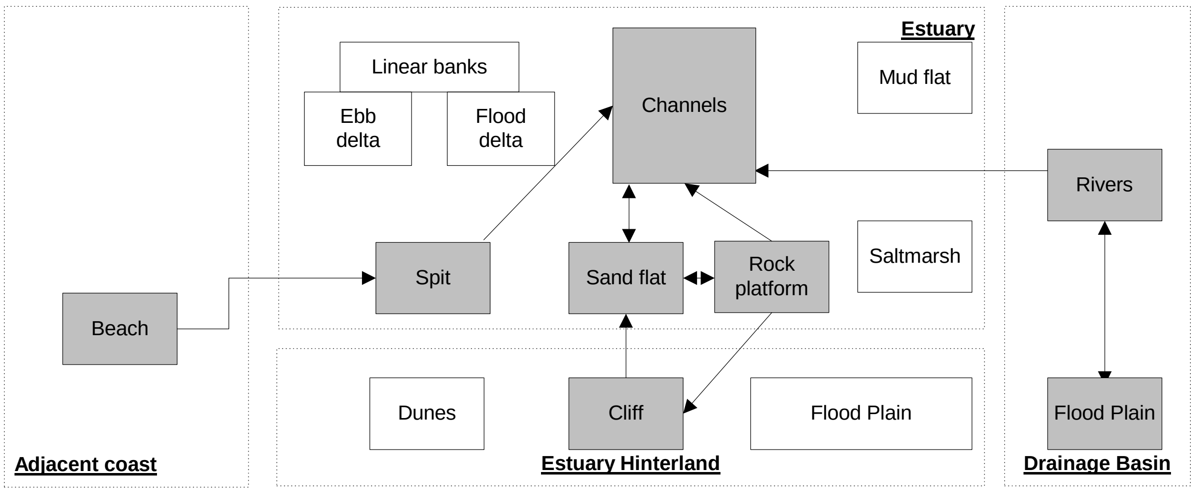


Figure 11. Generic fjord

5.2 Estuarine Behavioural Type 2: Fjard

Fjards are indented, drowned features fringing rocky, glaciated lowlands. Whilst they do not posses the deep glaciated troughs of a fjord, they generally reach greater depths than a ria. They generally have only small but highly seasonally variable river flow and have greater potential than fjords for the creation of spits at their mouths. Pwllheli Harbour in Wales is an example of a very small fjard with spits.

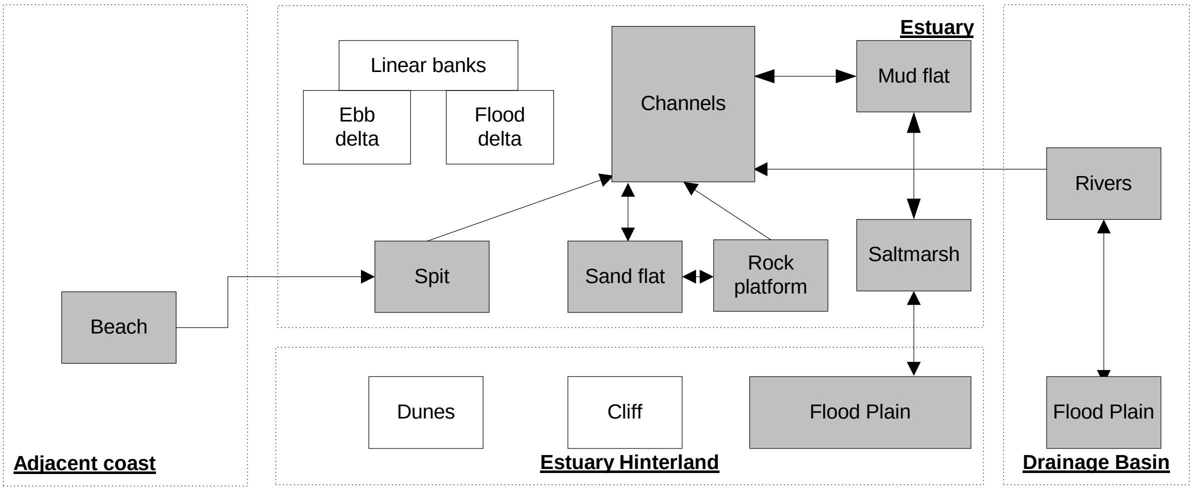


Figure 12. Generic fjard

5.3 Estuarine Behavioural Type 3: Ria

Rias are drowned valleys located in periglacial areas (that is areas which have been subject to cold climates, but not directly subject to glacial processes), with the original valley being created by fluvial process. Typically, rias are 'v-shaped' in cross-section, with the valley sides being relatively steep and composed of hard rock. In plan form, they exhibit the meandering form that is characteristic of other types of river valleys. Examples of rias with (e.g. Wear) and without (e.g. Tweed, Tyne) spits are common in northeast and southwest England and Wales.

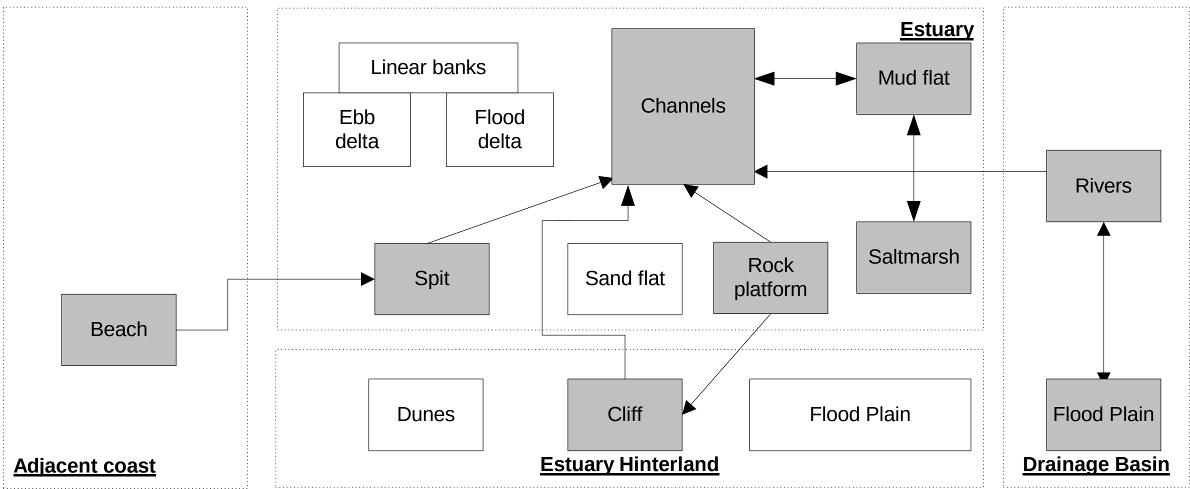


Figure 13. Generic ria

5.4 Estuarine Behavioural Type 4: Spit-enclosed Drowned River Valley

River valleys composed of soft rocks generally possess a more subdued relief than is experienced in harder rock areas, but have been subject to the same marine inundation processes caused by post-glacial (Holocene) sea-level rise. Many such areas possess drowned river valleys that have single or double spits at their mouths that tend to limit the mouth width and the physical processes occurring there. Many spit-enclosed estuaries, whilst experiencing high tidal velocities through their mouths, observe limited wave penetration due to the shelter provided by the spit(s) and at low water, salinity levels can be very low. Often, spit-enclosed estuaries have flood and ebb tidal deltas and many examples of spit-enclosed drowned river valleys exist throughout eastern, southern and southwestern England (e.g. the Teign), with the largest being the Humber, which has a single spit.

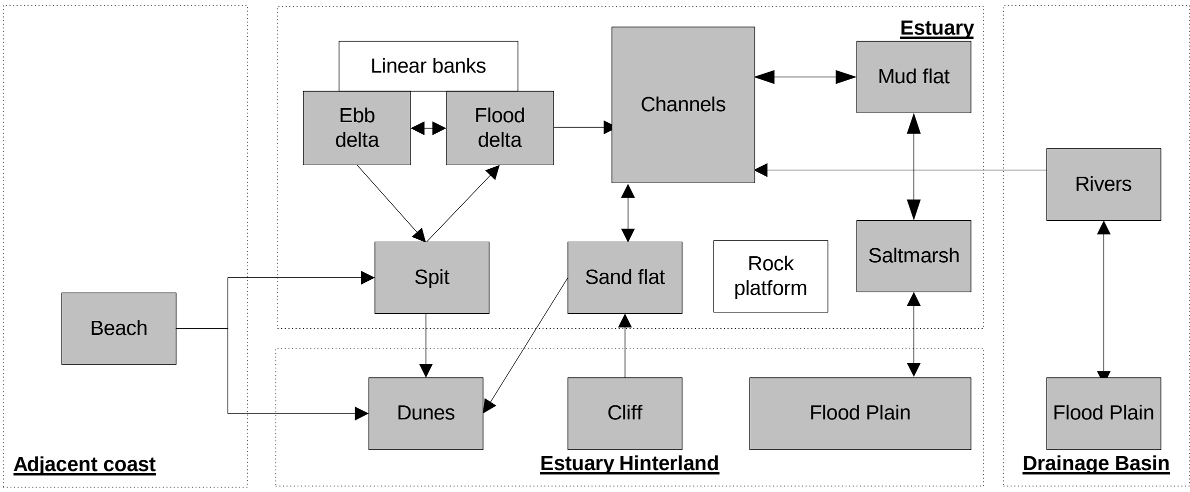


Figure 14. Generic spit-enclosed drowned river valley

5.5 Estuarine Behavioural Type 5: Funnel-shaped Drowned River Valley

Funnel-shaped estuaries are considered likely to be close to the classical definition of equilibrium form. They do not possess spits, indicating a strong tidal motion and relatively weak littoral drift of sediment from the adjacent coasts. Often such estuaries will posses elongated linear sand banks within the area of the estuary mouth, aligned parallel to the current flow direction. The area of the estuary mouth can, in some cases, cover a large region. The rivers Thames and Ribble are examples of funnel-shaped estuaries.

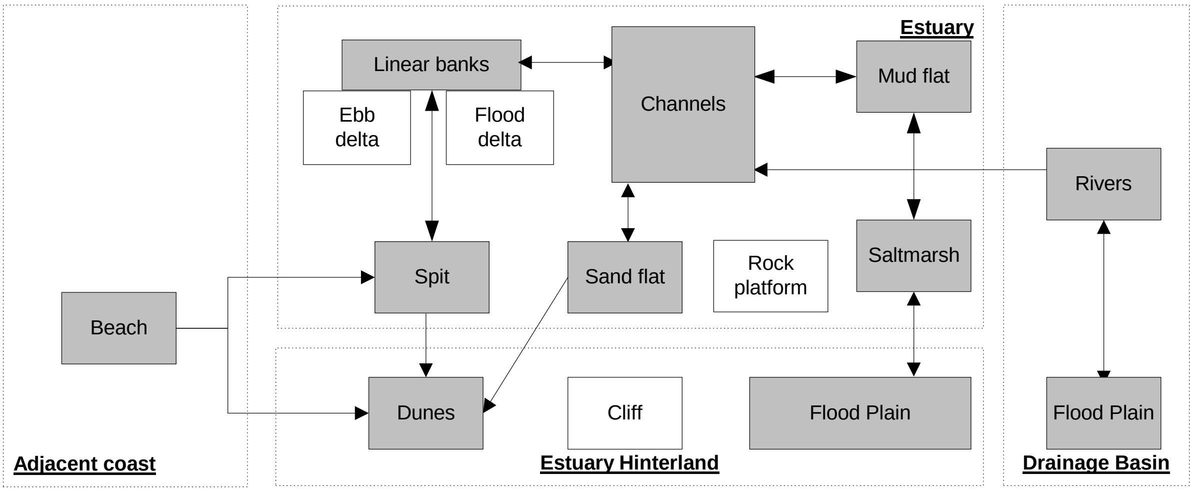


Figure 15. Generic funnel-shaped drowned river valley

5.6 Estuarine Behavioural Type 6: Embayment

Embayments are formed where several rivers converge and their joint valleys create a wide mouth area open to large wave and weather effects. They are characterised by large inter-tidal areas and high salinity throughout the embayment at high water. The Wash is a classic example of an embayment.

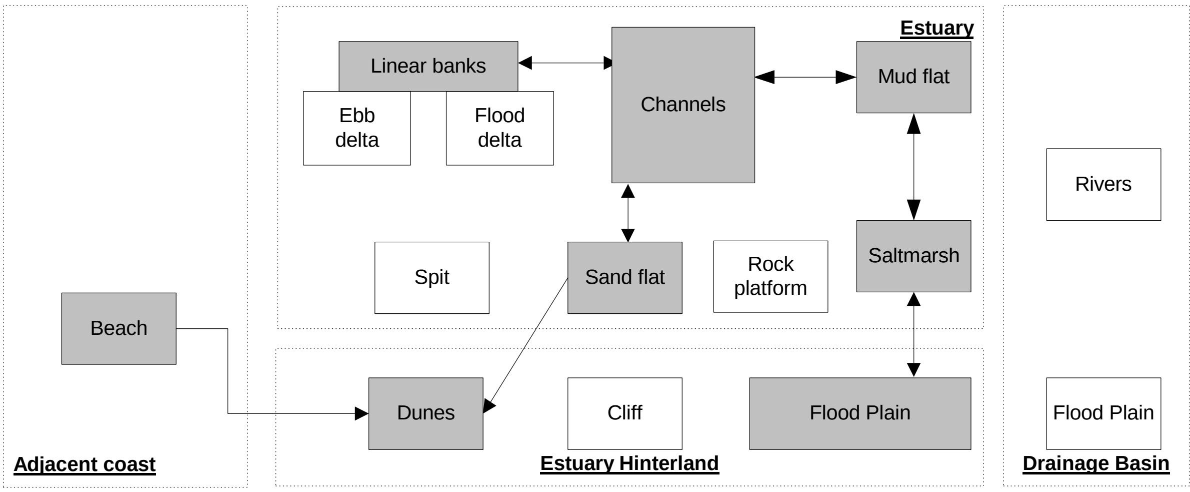


Figure 16. Generic embayment

5.7 Estuarine Behavioural Type 7: Tidal Inlet

Tidal inlets are produced where the relative sea-level rise has occurred over an extremely low relief coastal plain. These are characterised by narrow channels through fronting barrier beaches, and are backed by extensive tidal lagoons. In more tidally dominated areas, the inlet channel will typically be perpendicular to the coast, whilst in more wave-dominated areas the channel may be more obliquely aligned. Several examples of tidal inlets exist in close proximity along the south coast of England, namely at Portsmouth, Langston, Chichester and Pagham Harbours.

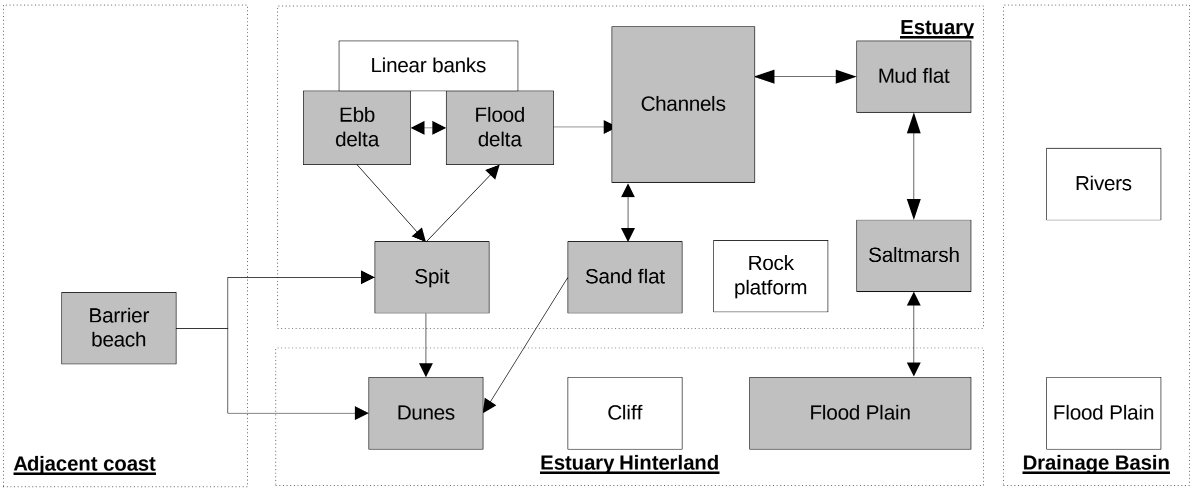


Figure 17. Generic tidal inlet

6. CASE STUDY BEHAVIOURAL STATEMENTS

6.1 Introduction

In addition to the generic work presented in the previous section, behavioural statements have been developed for two specific estuaries as case studies. The purpose of this exercise is two-fold:

1. To provide case studies, expressed in behavioural systems terms, to assist in the mathematical formalisation to be undertaken within the next project objective. In this sense the case studies will allow any behavioural models that are developed to be tested against known responses;
2. The behavioural statements work completed and presented in previous sections has concentrated on defining the characteristics and behaviour of estuary types and individual geomorphic elements at a generic level. The development of behavioural statements for two specific estuaries provides example of the output from the application of behavioural statements to specific UK estuaries.

The two case studies selected and developed are Southampton Water and the Humber. This selection was based on the fact that both estuaries are known to possess good datasets and have been the subject of considerable study in the past. The format that has been developed for presenting the case study behavioural statements draws on a number of aspects of the work completed and presented in previous sections of this report. In common with the previous approach, information is provided within the behavioural statements at two levels of system abstraction:

1. The whole estuary scale;
2. Individual geomorphic elements.

The rule base and estuary classification is first used to define both the estuary type and the specific geomorphic elements present within the estuary. Based on this information, a systems diagram is presented for the estuary in question, highlighting the elements present and the key linkages. At this estuary wide scale, a textural description is provided capturing the key characteristics of the estuary and the influences on behaviour. For each geomorphic element identified as being present within the estuary, a textural description is then provided, discussing the behaviour of the feature over a range of timescales. The timescales over which behaviour is discussed, is as follows (as per Section 4.5):

- Short Term (responses within a year);
- Medium-term (responses over decadal to century scale changes);
- Long-term (Responses over decadal to Holocene timescales, i.e. up to the last 10,000 years).

It is important to note that the work presented within previous sections of this report focused on characterising systems behaviour of estuaries over various scales at a generic level. In doing this, the definitions of behaviour have, by necessity, assumed a natural estuary system (i.e. a system with no anthropogenic intervention). In developing case study behavioural statements applicable to specific estuaries, it is inherent that these statements include the role of anthropogenic activities as these will have undoubtedly exerted an influence on past behaviour and will continue to exert an influence. Indeed, the inclusion of anthropogenic influences is a key aspect of the application of behavioural statements to specific estuaries.

The textural descriptions over the timescales outlined above draws on a variety of previous work on each estuary. This work has been synthesised according the geomorphic element and timescale and therefore full details of the key analysis that the statements are based on is not presented. To overcome this, an Annex is presented for each statement providing a summary of the key analysis for that estuary, including quantification where appropriate, along with a comprehensive reference list. The intention is therefore to provide a user with a understanding of the estuary, in systems terms, together with further quantification from specific analysis and references.

The case study statements for Southampton Water and the Humber are presented in Appendix L and M respectively.

7. ESTSIM UTILITY

The estuary classification and the application of the protocol and has generated a good definition of estuary environment in systems terms. In addition to presenting this information within the report, a framework (or 'utility') has also been developed to link the information together and allow a user to navigation through the statements to extract information and understanding at different levels.

The utility is essentially a PC based data catalogue and viewer, providing a tool to access the various estuary specific and generic outputs generated within Objective 3, Behavioural Statement and presented within this report. Details of the utility, its content and functioning are presented within this section.

7.1 Content

The utility provides the framework with which to view a number of the outputs and Generic behavioural statements have been produced at different abstraction levels as follows:

1. At the higher level, the seven estuary behavioural types are defined, identifying the geomorphic elements present within each of these types and how they link;
2. At the next level down, each identified geomorphic elements are defined in greater detail.

In addition to this generic information site specific details have also been produced:

1. Two case study behavioural statements (The Humber and Southampton Water);
2. Classification of UK estuaries according the seven generic estuary types (including representation of the geomorphic elements present in the estuary type and the specific estuary).

The utility has been developed to provide the framework to hold these four sets of information, allowing navigation through the information to obtain outputs relating to both generic aspects of estuary systems and specific details of UK estuaries.

7.2 Design

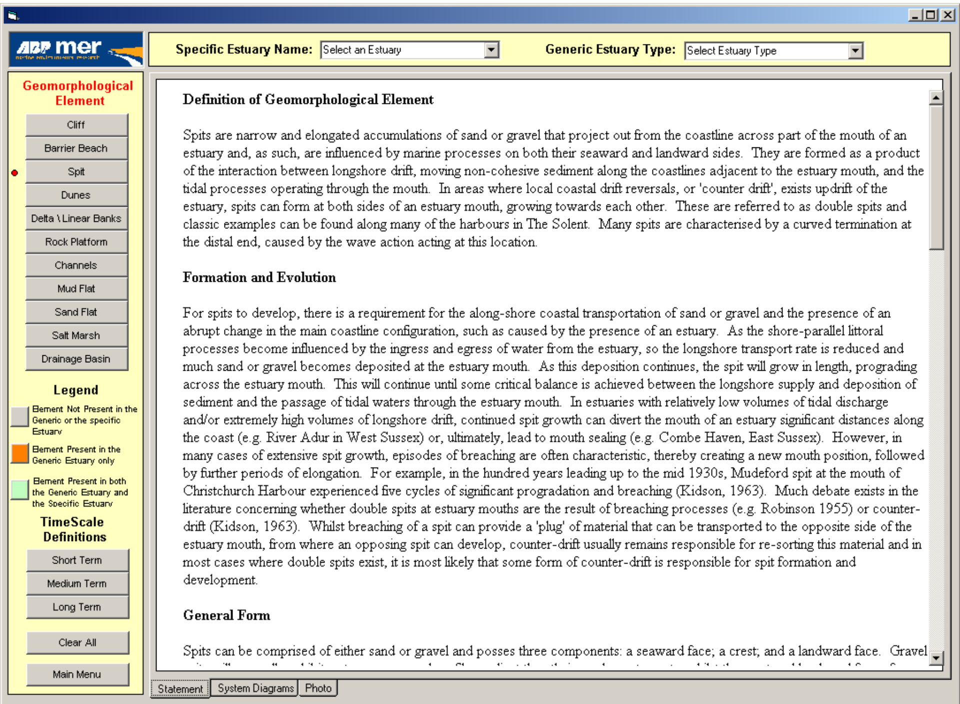
When considering the development of a system for EstSim, which would allow the data held in the Estuaries Database to be used, it was recognised at an early stage that a structured approach would be required. It was therefore decided that the Structured Systems Analysis and Design Methodology (SSADAM) would be the most suitable approach. This approach is a widely regarded and respected analysis technique designed and used by the Government for systems analysis and design. The flexible approach was also fully adaptable to proposed system.

7.3 Structure

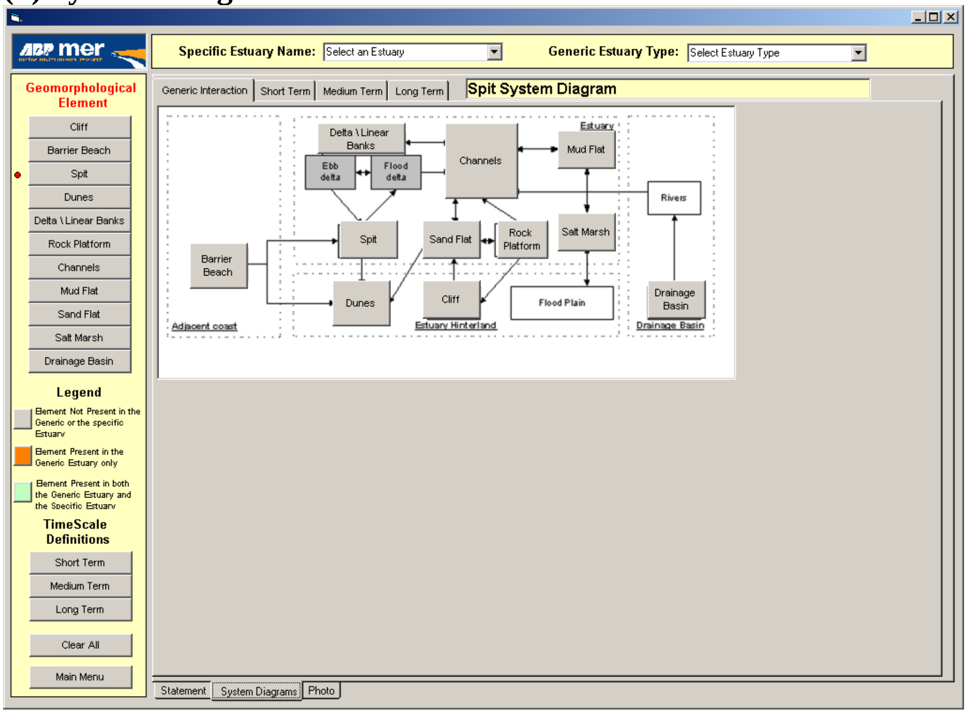
The system itself has been created in Visual Basic 6 and functions as a data catalogue and viewer. The application works by first loading relevant information such as, estuary names and geomorphological content, from the Estuaries Database. Once loaded the application allows the user to view this data as well additional related information in the form of documents, photos, maps and system diagrams. The additional data files are simply linked to various features within the application and are retrieved by user driven requests. Some example windows from the Utility are provided in Figure 18.

Figure 18. Example windows from the EstSim Utility

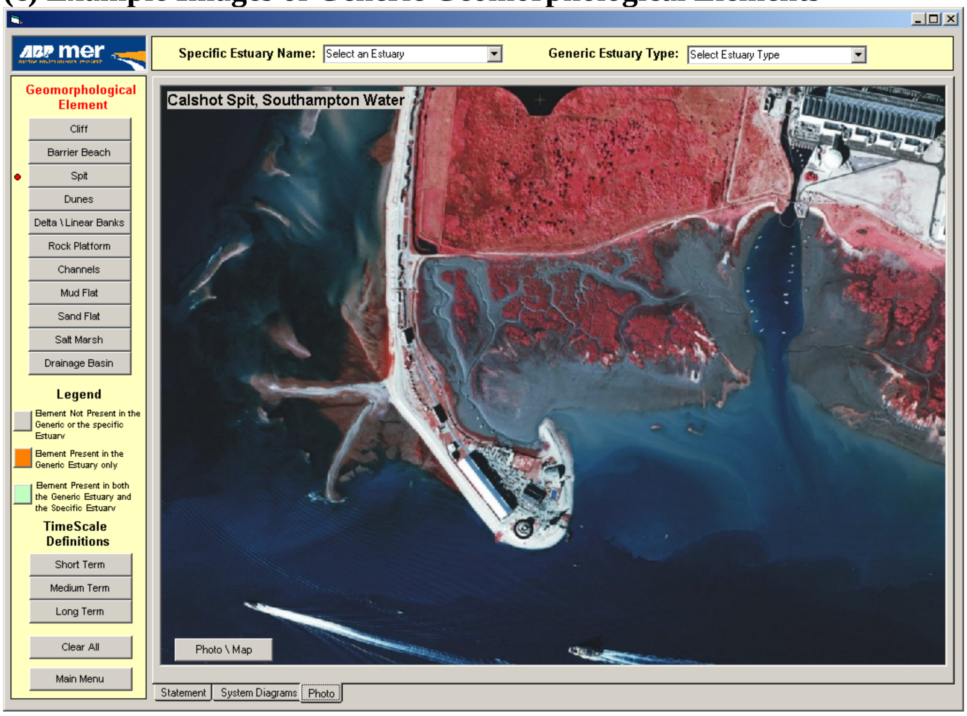
(a) Generic Geomorphological Element: Behavioural Statements



(b) Systems Diagrams



(c) Example Images of Generic Geomorphological Elements



8. THE WAY FORWARD (FUTURE OBJECTIVES)

Objective 3, Behavioural Statements, has provided formal definition of estuarine systems. The next stage of the project (Objective 4, Mathematical Formalisation) involves developing the behavioural statements into a logically consistent mathematical framework. Subsequent to this, Objective 5 (System Simulation) will then set up the system simulation based on this formalisation.

In order to facilitate the translation of the outputs from Objective 3, as presented within this report, into a way forward for Objective 4, a Translation Workshop was held on 14 December 2004. Project partners and Defra's project officer attended the workshop. The work completed within Objective 3 was presented at the meeting and the participants discussed both this and how it could be translated into the next objective.

The purpose of the workshop was therefore two-fold:

(a) Reach a consensus regarding the work required to finalise Objective 3 and the Behavioural Statements Report (Project Record PR2); and
(b) Reach a consensus regarding the approach to be adopted in the initial development of Objective 4, Mathematical Formalisation.

8.1 Objective 3: Behavioural Statements

The project partners and Defra's project officer were provided with a draft version of this report prior to the translation workshop to allow the contents of the document to be reviewed and form the basis for discussions. There was agreement within the project team that the report achieved its overall aim of providing the formal definition of the estuary system in terms of the systems approach. Importantly the report was also seen as characterising the relationships, in the form of behavioural statements, required to progress the next phase of work.

A discussion was held regarding the ability of the behavioural statements presented (both in the textural descriptions and the accompanying systems diagrams) to characterise systems behaviour. It was recognised that the flowcharts used to produce the systems diagrams may be limited in their ability to represent all the interactions present within a given system component. However, the approach allows the key relationships and linkages that determine behaviour to be captured. It is these key interactions that are required to allow mathematical formalisation. From this point of view therefore, the behavioural statements provide a mapping of an estuary system and its components that capture and present behaviour in a format that can be taken forward within the next phase of the project.

In addition to the overall discussion of the work completed within Objective 3, a number of specific comments were made regarding the report and potential minor amendments. Project partners were requested by provide specific comments in writing to allow these to be incorporated into the final version. Comments were subsequently provided by a number of partners and Defra's Project Officer. These comments are incorporated into this final version of Project Record PR2.

8.2 Objective 4: Mathematical Formalisation

The objective of this project task is to develop the behavioural statements (Objective 3, as presented within this report) into a logically consistent mathematical framework. The task is being led by the University of Plymouth, with input from other members of the team as appropriate. Work on this element commenced following the translation workshop and is scheduled to continue until April 2006.

During the translation workshop (14 December 2004) discussion was held regarding how to approach formalising the relationships defined within Objective 3. To facilitate this discussion, Prof. Rob Seymour (Professor of Mathematics, UCL) was invited to present work he is currently progressing relating to estuaries. Prof. Seymour's work is being undertaken independently of the EstSim project, however, the nature of the work and the approach being adopted is of relevance to the systems approach being developed within this project.

A decision was made to progress the initial investigations within Objective 4, based on a Boolean approach. This approach will initially be used to analyse the response to an element of an estuary or estuary type to a change in physical forcing, such as a change in wave energy or tidal energy. The intention is initially to develop this approach at a generic level in an attempt to characterise the relationships defined within Objective 3.

More specifically the approach, involves using Boolean variables to represent the different elements of the estuary and physical forcing factors (such as tides, waves etc). The response of a variable to a given change can be provided by a Boolean function, using a set of logical equations. Initially this will be developed for each of the individual generic geomorphic elements defined within Objective 3. These geomorphic elements will then be combined to form a network, representing a generic estuary system (based on the generic estuary types defined within Objective 3).

The work undertaken within this Mathematical Formalisation Objective has important implications for the approaches and development within later objectives, not least the System Simulation task. For this reason two further workshops were arranged through the course of Objective 4. A progress meeting is to be held in April 2005 to provide an opportunity for initial progress on the task to be presented to the team by University of Plymouth. In addition a Translation workshop remains scheduled for Late August/early September 2005.

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APPENDICES A-M

Appendix A: Behavioural Description for Cliff

Definition of Geomorphological Element

Cliffs are defined as vertical or steeply sloped faces, forming a distinct break in slope between the land and the shore. Sea cliffs can be found along the open coast, sometimes close to an estuary mouth, and glacially formed cliffs can form the boundaries of some types of estuary valley. Coastal slopes (or bluff) are similar, but of a generally lower gradient. Both types of feature can be active (i.e. exposed to marine action) or relict (i.e. formed during previous stages of (higher) relative sea-level history and now left stranded).

It is important to note that sea cliffs and slopes are not only affected by marine action (e.g., waves, tides and currents acting at their toe), but also by sub-aerial (weathering) and sub-surface (groundwater) processes which act upon the slope above the limit of wave action. Indirectly, sea spray may affect the sub-aerial processes; indicating the complexities associated with gaining an understanding of the processes to which a sea cliff or coastal slope may be exposed.

Function

In terms of their primary function within an estuary, cliffs act as a boundary to the overall system. Within certain types of estuary valleys, the cliff or coastal slope may limit the extent of marine inundation (and by implication, may impede transgressive 'rollover' of the estuarine intertidal during a rise in sea-level).

In addition to this, cliffs can also supply sediment to an estuary system, although this is very much dependant on the nature of the cliff and the degree of exposure. This function dictates that cliffs are, by their very nature, an erosional landform.

Formation and Evolution

Cliff or slope recession is initiated when the stresses acting on the feature exceed the shear strength of the material. This situation may arise due to a combination of a number of factors. In basic terms, these comprise external factors which may exist or occur which increase the shear stresses applied or internal factors which may exist or arise which result in a decrease in the shear strength of the material.

Evolution is also highly dependent on the rate of supply of material to the cliff or slope toe from the face relative to the rate of removal of this debris by wave or tidally-induced currents at the cliff base. The variations in resultant form of cliffs can be illustrated by considering two extreme scenarios. Firstly, in a system where the rate of supply of debris is considerably greater than the rate of its removal from the cliff base, debris material will accumulate over a period of time. This results in the creation of a talus slope with a profile angle consistent with the angle of repose of the debris material. This form is produced most frequently in sea cliff systems that experience a rotational mass movement and the overall sea cliff slope angle decreases as a result.

In the opposite extreme case, where the rate of material input from sea cliff erosion is considerably less than the rate of removal of debris from the cliff toe, the sea cliff slope will retreat whilst generally maintaining a constant slope profile angle. The actual slope angle and rate of retreat will depend upon the lithology of the material of which the cliff is comprised. An example of the typical recession rates in rock materials of different lithology is presented in Table A1.

Table A1. Typical recession rates of cliffs composed of different materials (After Sunamura, 1983)

Cliff Composition	Typical Recession Rate (m per year)
Granite	< 0.001
Limestone	0.001 to 0.01
Shales	0.01
Chalk	0.1 to 1
Tertiary sedimentary (sandstone, mudstone)	0.1 to 1
Quaternary sedimentary	1 to 10
Recent volcanic	10 to 100

The strength of the rock plays an important role in the pattern and rates of cliff or slope erosion throughout the UK. For example, in broad terms, the sea cliffs formed of relatively hard rock comprise a steep face and are presently retreating very slowly where marine erosion and cliff recession are of limited frequency and often small scale. Such cliffs may be fronted by a boulder apron, narrow beach, rock platform or plunge directly into deep water. In contrast, intense marine erosion and cliff recession rates occur on the unprotected cliffs or coastal slopes formed of soft sedimentary rocks and glacial (drift) deposits along the south and east coasts of England.

General Form

It has been suggested (MAFF, 1996) that for a particular geological setting and set of environmental conditions there will be a characteristic set of recession processes (cliff behaviour) giving rise to characteristic cliff forms, as defined below and illustrated in Figure A1 below:

Simple Cliff Face Systems
These systems are generally characterised by a steep cliff face, narrow foreshore zone and rapid removal of toe debris. Erosion typically occurs as rockfalls, topples or slides from which material is deposited directly on the foreshore.

Simple Landslide Systems
These systems are first time failures in previously un-sheared ground, or repeated failures in recently sheared ground. Toe erosion of cliff debris leads to oversteepening of the cliff face and a deep seated rotational slide develops.

Composite Systems
These systems typically comprise inter-bedded hard and soft rocks. This can generally be as either soft rock caps resting on hard rock or as hard rock caps resting on softer rock. The latter case presents greater sensitivity to recession.

Complex Systems
These systems comprise a series of sub-systems, such as scarp and bench features, within the cliff. Each sub-system has its own input, storage and output of material, whereby the output from one sub-system forms a cascading input to the next. There can be some considerable time lag before material reaches the cliff toe.

Relic Systems
These systems comprise sequences of pre-existing landslides, which are presently subject to relatively little recession, but could be susceptible to re-activation due to debris removal, foreshore lowering or increasing porewater pressure.

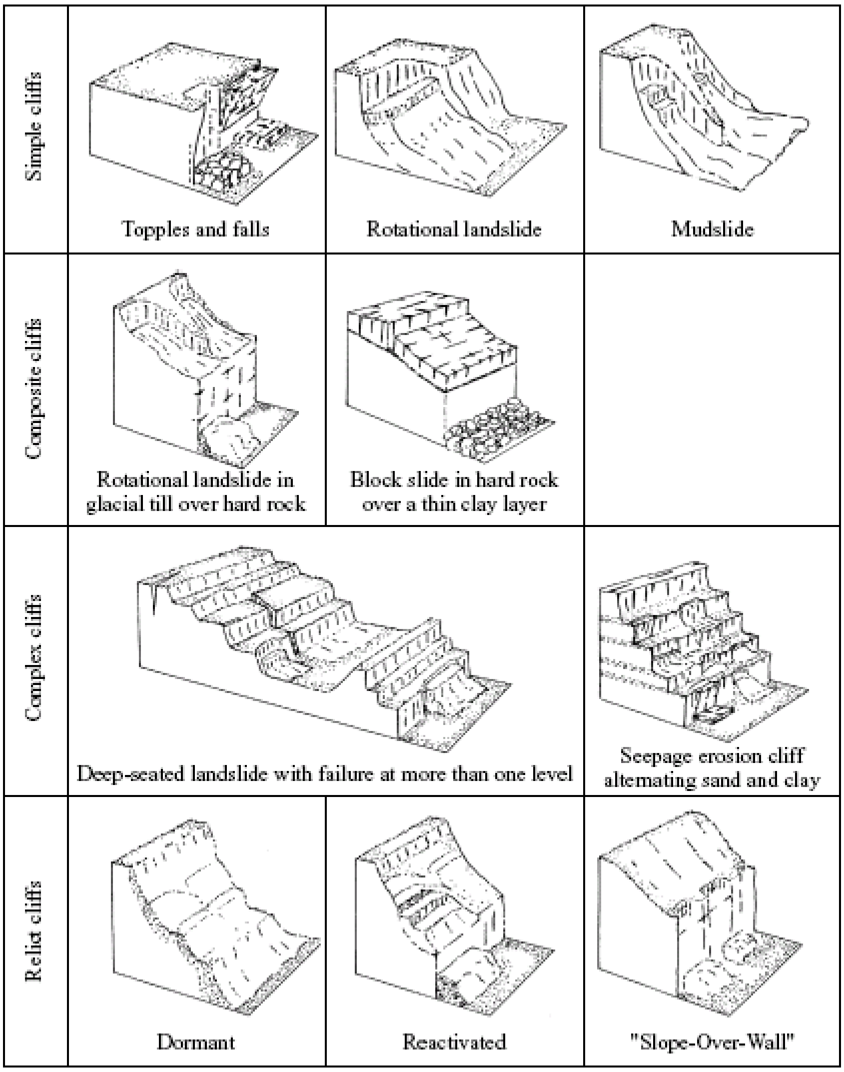

Figure A1. Characteristic Cliff Behaviour Unit Types (MAFF, 1996)

Sub-features - Caves, Arches and Stacks
Differential erosion between relatively resistant and relatively erodable cliff materials can result in the creation of caves, arches, stacks and other related sub-features. Such features often are the result of accelerated erosion along structural weaknesses, particularly bedding, joint and fault planes, and in the fractured and crushed rock produced by faulting. These features form in rocks, which, despite containing weaknesses, have sufficient inherent strength to stand as near vertical faces, or as the roofs of caves (Trenhaile, 1997).

General Behaviour

In general terms, sea cliff behaviour displays a number of important components. Firstly, unstable conditions will be created within the cliff, possibly due to any one, or any combination, of the following: foreshore lowering and undercutting of the slope base by marine action, possibly leading to over-steepening of parts of the cliff face; sub-aerial weathering; increase in groundwater pressure). Following "triggering events" such as storms and/or intensive rainfall, material becomes detached from the cliff and is transported, via a number of potential mechanisms, to the foreshore near the cliff base. This debris is deposited and accumulates, providing a degree of protection to the cliff base against direct wave action until, ultimately, it is removed by marine processes and re-distributed elsewhere within the coastal system.

Unlike many other coastal landforms (e.g. beaches, tidal flats), sea cliffs cannot experience regression (a seaward advance of the landform whilst maintaining a constant profile through the deposition of sediments) in response to changing environmental conditions.

Sea cliff recession will depend upon a number of factors, which may:

- Promote mass movement of cliff material; and
- Control the rate of removal of debris from the cliff base.

Forcing Factors

The principal forcing factors are marine erosion, weathering and groundwater conditions.

The amount of marine erosion is dependent upon the balance between the shear strength of the material in the cliff or slope and its exposure to waves and tidal currents, which generate shear stresses. The magnitude of these stresses is dependent on the exposure of the site, which is governed by the offshore conditions, its water depth and nearshore topography, and the degree of protection offered by the fronting inter-tidal area (e.g. inter-tidal beach or flat, shore platform).

Weathering can take two main forms, namely corrosion (the chemical alteration (or decomposition) of the rock by salt water) and corrosion (the mechanical weathering (or disintegration) of the rock by abrasion). Mechanical weathering may more rapidly break down large pieces of rock, which then become subjected to increased rates of chemical weathering. Mechanical weathering may be caused by a number of factors (e.g. mechanical loading/unloading; thermal loading/unloading (e.g. cycles of freeze and thaw); wetting and drying cycles; pressure effects from salt crystal growth; and root wedging. Chemical weathering too may be caused by a number of factors (e.g. solution; oxidation; reduction; hydration; hydrolysis; leaching; cation-exchange), which serve to alter rock crystals, sediment grains or the cements, which bind grains together (Blyth & de Freitas, 1984). In combination, these may:

- Create fissures and enlarge joints, thereby reducing the strength of the cliff-forming materials;
- Create pathways for the ingress of water into soft rocks, thereby aiding in the process of decomposition;

- Cause small movements which tend to reduce shear strength;
- Provide sufficient stresses to trigger failure.

Changes in groundwater conditions within certain types of cliff or slope can be a major triggering factor of landsliding. The voids (or pores) between particles of sediment are filled with fluid (water or air). The pressure of the fluid within the pores can increase due to periods of long and intense rainfall, snowmelt, groundwater seepage, undrained loading, blockage of subsurface water flow, poor surface water disposal and leakages from pipes. This can lead to the promotion of instability within the cliff, although a time lag between the perceived cause and the actual event is common.

In addition, biological factors may also reduce the strength of rocks. Examples include: boring and grazing of coastal rocks by marine organisms; and the growth of plant roots into joints and bedding planes. Biological weathering is rarely a triggering factor in cliff recession, but assists in preparing a cliff for failure by slightly reducing its material strength. It should be noted, however, that biological factors may also enhance stability of soft cliffs, through the binding of material within plant roots. Indeed, stabilisation programmes involving cliff vegetation through the use of engineered swards have been used in southern England (Tyhurst, 1996).

Evolutionary Constraints

At the most fundamental level, cliff or slope recession is constrained by:

- The strength of the material in the cliff or slope;
- The stresses applied to the cliff or slope; and
- The rate of removal of debris from, or foreshore lowering at, the cliff or slope toe.

Behavioural Timescales

Short-term (responses within a year)
When considered over the short-term, cliff behaviour appears episodic, complex and uncertain. Behaviour is often characterised over this timescale by no change along many cliff sections with relatively localised failures in one or two particular locations in response to lowering foreshore levels and/or increasing pore water pressure.

Medium-term (responses over decadal to century scale changes)
Over the medium term, more uniform patterns of recession emerge, as the entire cliff appears to move landwards.

Long-term (Responses over decadal to Holocene timescales)
Over the longer-term (e.g. centuries), cliff behaviour may be controlled by larger-scale plan form evolution such as the creation of embayments within headlands.

Interactions with other Geomorphological Elements

General Interactions (Elements within estuary system)
A proportion of the material released from cliff or slope erosion may be relatively coarse, non-cohesive sand or gravel of a sufficient size and composition to contribute to the debris

stock of sediment at the cliff or slope toe. Ultimate re-distribution of this debris may result in material contribution to beach building or feeding of offshore bars, barrier beaches or spits elsewhere in the coastal system. Also, a proportion of the material released from cliff erosion may be fine, cohesive silts and clays of a size and composition which results in their immediate suspension in the water column and transport offshore or along the coast to feed estuaries and their tidal flats and saltmarshes.

It is also important to recognise that cliffs and slopes are also afforded a degree of natural protection against marine action by the fronting inter-tidal zone (beach, tidal flat, rock platform and, occasionally, saltmarsh). These features dissipate, refract and reflect incoming energy (generated by waves and tides) and reduce the amount of energy that reaches the toe of the cliff or slope. A classic study by Savigear (1953) attributed a spatial transition from marine to subaerial cliff profiles within Carmarthen Bay to a progressive reduction in wave energy resulting from the extension of the Laugharne Spit and the growth of saltmarsh. Alternatively, the presence of coarse sediment within the breaker zone may reinforce wave erosion as a positive feedback mechanism.

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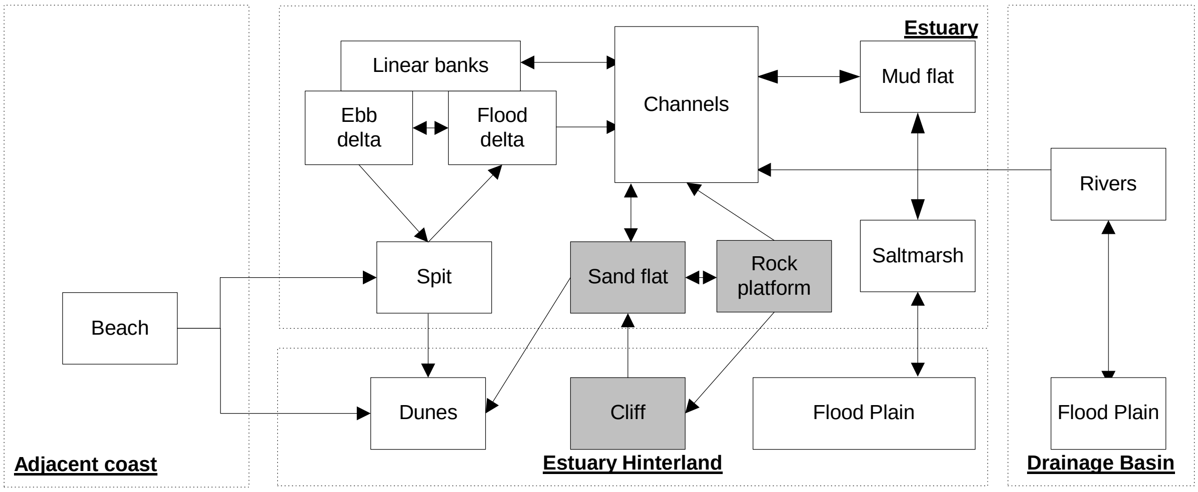
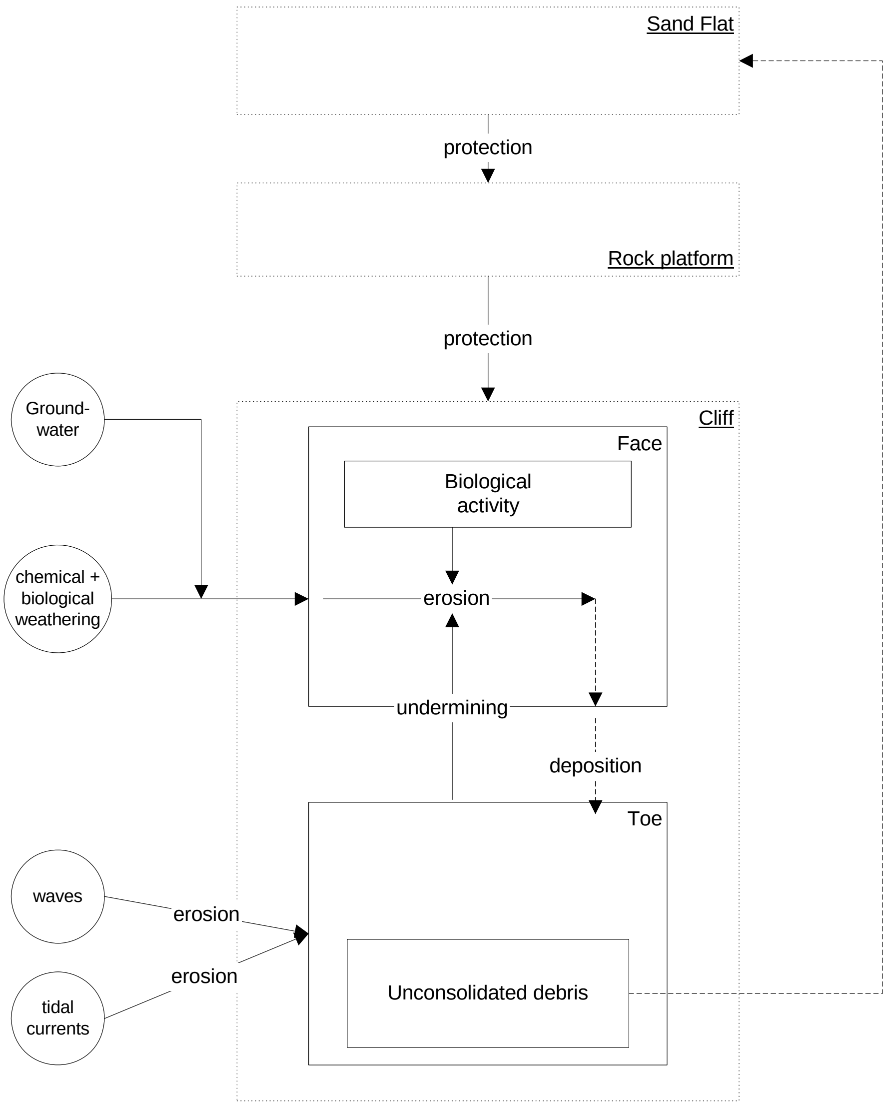
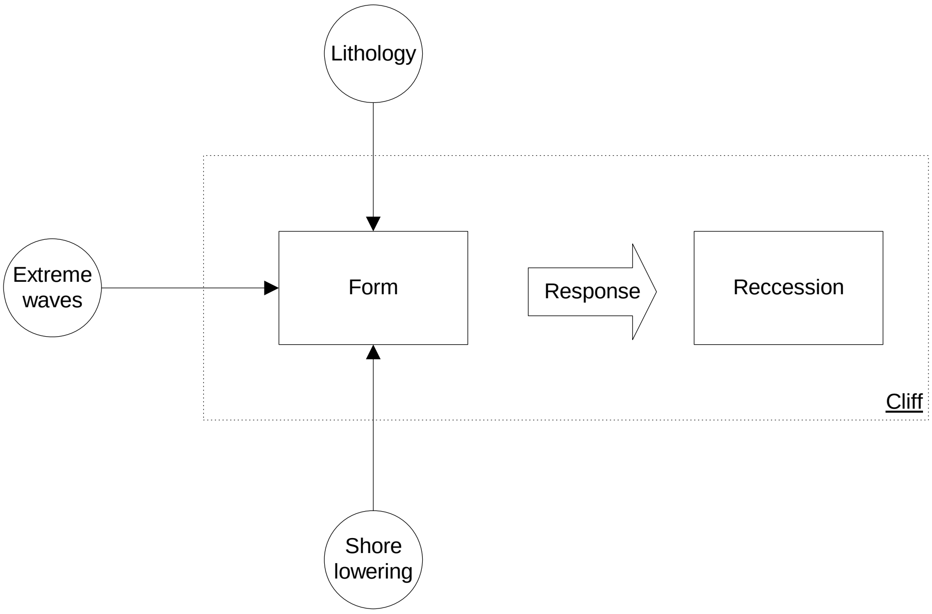
Interaction with other elements - Cliff



Short to medium term system diagram - Cliff



Medium to long term system diagram - Cliff



Appendix B: Behavioural Description for Barrier Beach

Definition of Geomorphological Element

Barrier beaches are narrow and elongated accumulations of sand and/or shingle fronting low-lying hinterland. Barrier features can become breached during severe storm events, leading to the creation of a tidal inlet if the breach is not sealed by either natural processes or by management intervention. A recent UK example is the breaching of the Porlock gravel barrier in Somerset in October 1996, which has led to the creation of a new tidal inlet.

Function

The function of barrier beaches is to provide a 'barrier' against tidal flooding to the hinterland. This is achieved by means of tidal and wave energy dissipation and physical blocking of rising tidal levels.

Formation and Evolution

Typically barrier beaches can be formed either by the breaching of a spit or by the emergence and subsequent enhancement and landward transgression of an initial bar, built by constructive wave action. In the latter case, the barrier formation started as relative sea-levels rose during the Holocene and swept up sediments lying on the present-day seabed, transporting them landwards where they accumulated sufficient sediment volumes to form bars that then further developed into barriers. As relative sea-levels continued to rise, so the barriers transgressed landwards until their interception with rising topography, such as sea cliffs, to form inter-tidal beaches. In areas where the topography is low-lying, the barriers remain in a transgressive mode in response to continued relative sea-level rise. Due to the relative exhaustion of seabed sediment stocks, most barriers are contemporarily fed with sediments by littoral processes.

Where barriers have become permanently breached, so a tidal inlet will form, with an associated inlet channel and ebb and flood tide deltas present. In these cases, the low-lying hinterland will revert to areas of sand flat, mud flat or salt marsh.

General Form

Barriers can be comprised of sand and/or gravel and posses three components: a seaward face; a crest; and a landward face. In addition, dunes may be perched on the barrier crest. Gravel barriers will generally exhibit a steeper seaward profile gradient than their sand counterparts, whilst the crest and landward face of either sediment class may be vegetated.

Sub components may include wash over fans and wash over flats, both of which are accumulations of sediment on the landward face of the barrier created by water flows pushing material over the crest.

General Behaviour

Under the presence of a sufficient supply of sediments, barrier behaviour will mostly be transgressive, with landward migration in response to rising relative sea-levels. This will occur through repeated processes of crest build up followed by episodic washover, with the over-flowing water pushing sediments from the crest to the landward face (Carter, 1988).

Where sediment supply becomes critically low, for example due to the provision of coastal defence works along adjacent updrift coastal frontages or exhaustion of seabed sediment stocks, the form of the barrier is likely to change from a drift-alignment to a more segmented, swash alignment.

Breaching may result from crest cutback due to erosion of the seaward face and crest, the lowering of crest levels during periods of overwashing, or a combination of both processes. Single or multiple breaches may develop. In the absence of sufficient longshore sediment supply, the breach can remain intact and a new tidal inlet can form (Orford *et al*, 1996). If longshore sediment supply is large (when compared against the flushing power of the new inlet), then the breach is likely to be ephemeral and naturally become sealed.

Overstepping occurs when the barrier is unable to maintain its entire form in response to increases in relative sea-level rise. In such cases, the barrier will usually become overwashed initially, with a base of material remaining on the seabed and the remainder of the material being dispersed by wave and tidal processes.

Forcing Factors

Barriers are subject to wave-driven longshore and cross-shore sediment transport processes, and, to a lesser extent, tidal processes. Where barriers are intact features protecting a low-lying hinterland, they can also be subject to hydraulic forces caused by seaward flow through the barrier of an excess water head caused by overtopping events or after periods of high intensity rainfall. In addition, the reverse process can also occur whereby seawater may cross a barrier from the seaward to the landward side, through seepage (Carter, 1988). This process is dependant on the nature of the deposits, with a significant role on gravel barriers due to their higher permeability and an insignificant role on sand barriers. The process of seepage can, in certain situations, reduce barrier stability and hence increase the potential for barrier breaching. Where breaches occur and a new inlet is formed, barriers become subject to marine processes on both their seaward and landward sides.

Evolutionary Constraints

The key constraints to barrier evolution are sediment supply and wave exposure, backshore characteristics and the rate of relative sea-level rise. Sediment supply is the key factor which dictates the health of the barrier and hence its susceptibility to breaching during periods of extreme wave activity. Where sediment supply is sufficient, it is likely that the barrier will be less susceptible to permanent breaching and tidal inlet creation and the barrier will remain more dynamically responsive to short-term and long-term pressures. However, where contemporary sediment supply is constrained, the barrier may be both more susceptible to breaching (due to reduced volumes of sediment within the barrier structure and a change in its planform morphology from drift- to swash-alignment) and less likely to naturally seal any breach that does occur.

The transgressive response of barriers to rising relative sea-levels will become constrained by rising topography as the barrier moves back to intercept such landforms. The topography of the hinterland is also important in the context of shallow depressions or channels, into which barrier sediments can transgress, effectively reducing the crest height of the barrier. The geological nature of the hinterland is also important as this too may influence the ability of the barrier to transgress. Additionally, the rate of relative sea-level rise may determine whether the barrier is able to transgress or whether instead it will become outpaced by relative sea-level rise and ultimately will be overstepped and break down.

Behavioural Timescales

Short-term (responses within a year)
Over the short term, barriers will exhibit dynamic responses to individual 'frequent' storm events and seasonal wave climates, with processes of cross-shore and longshore sediment movement occurring and changes in profile gradient and crest height observed.

Medium-term (responses over decadal to century scale changes)
Where wave activity is such that overwashing occurs, barrier sediment can be moved from the seaward face, to and then over the crest, to become deposited on the landward face, causing washover fans and flats to encroach on the hinterland. Overwashing can result in two potential responses: (1) beach roll-back and crest lowering or (2) crest roll-back and reforming at higher elevation (Bradbury, 2000). Over this medium term barrier behaviour will therefore be dominated by changes in vertical and horizontal position. The ability of a barrier to respond to changing forcing and migrate accordingly will depend on rate of relative sea-level change, sediment supply and the degree of wave exposure. In the case of a transgressive barrier response, the barrier could migrate across the hinterland, at a rate controlled by rate of relative sea-level rise, exposure to storm conditions, sediment composition and supply and hinterland topography and lithology.

Long-term (responses over century to Holocene timescales)
Over the longer timescale, barrier behaviour could cover a significant range of occurrences, from landward migration in response to modest relative sea-level rise, through breakdown processes (e.g. segmentation, washover, overstepping or breaching and new inlet formation) under conditions of reducing sediment supply and/or increasing wave exposure.

Interactions with other Geomorphological Elements

General Interactions (Elements external to the estuary system)
Barriers are fed with sediment from adjacent beaches by processes of littoral drift and from any available offshore sources. The latter process can occur as slow, progressive feed during periods of constructive wave action, or as a large pulse of sediment during storm conditions, which mobilise material from storage in offshore banks or deltas. However, such periods of storm activity can also cause barrier crest cut-back and temporary movement of sediment from the barrier to the lower foreshore. Periods of storm action can also result in offshore transport of sediments from a barrier

General Interactions (Elements within the estuary system)
When a barrier becomes breached, it will enable tidal waters to flood the hinterland and a new tidal inlet, with associated channels and ebb and flood deltas, to form.

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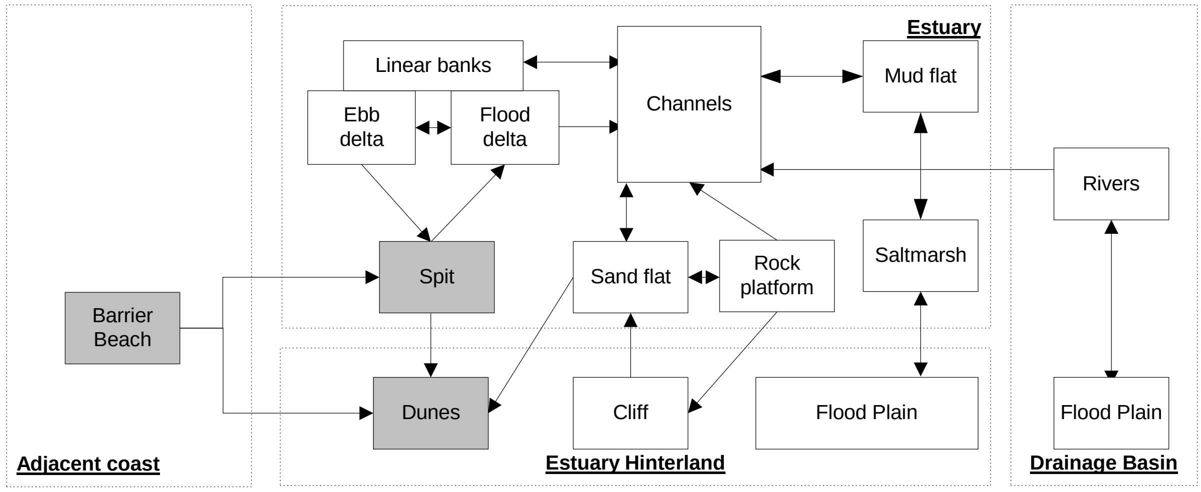
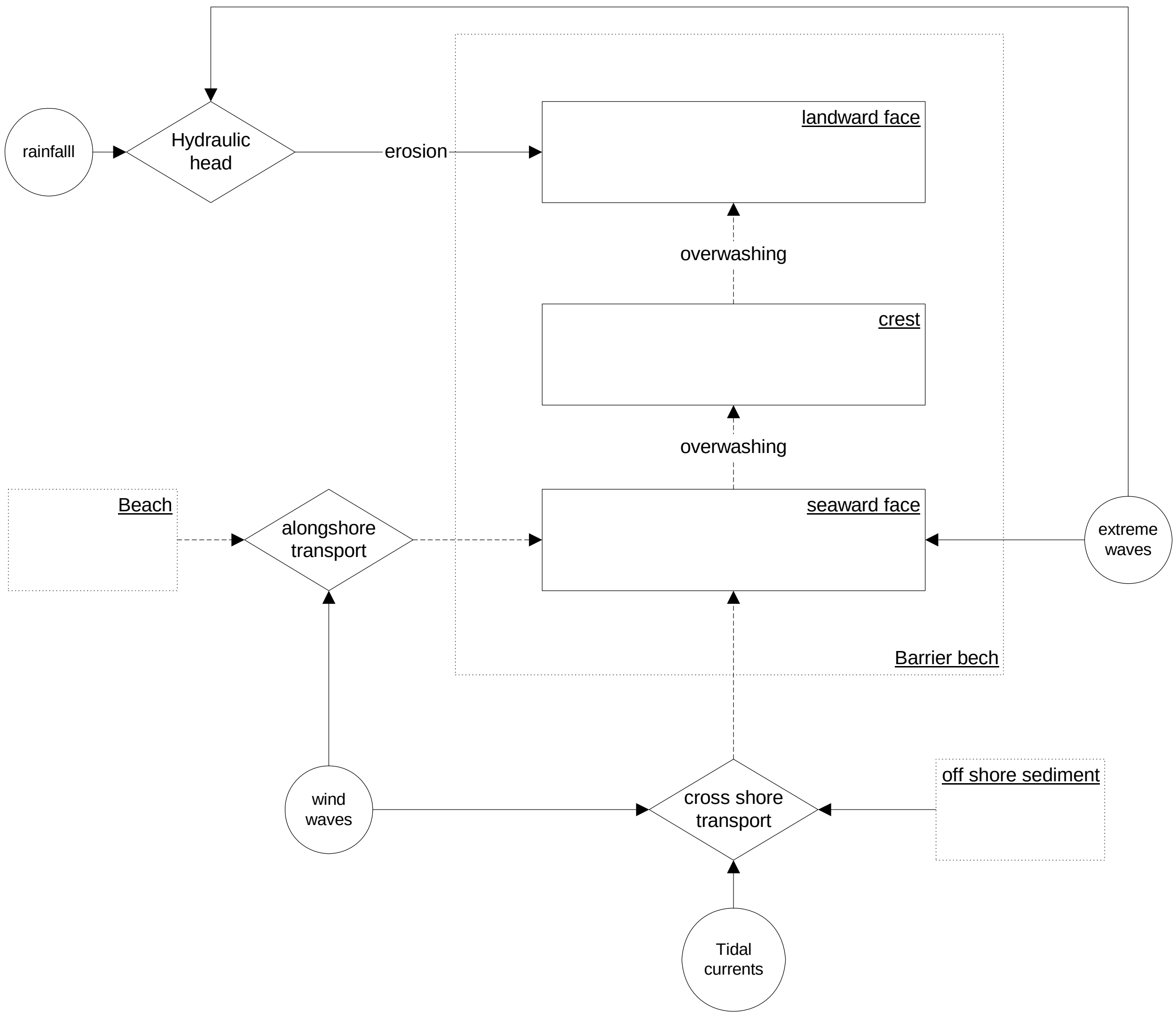
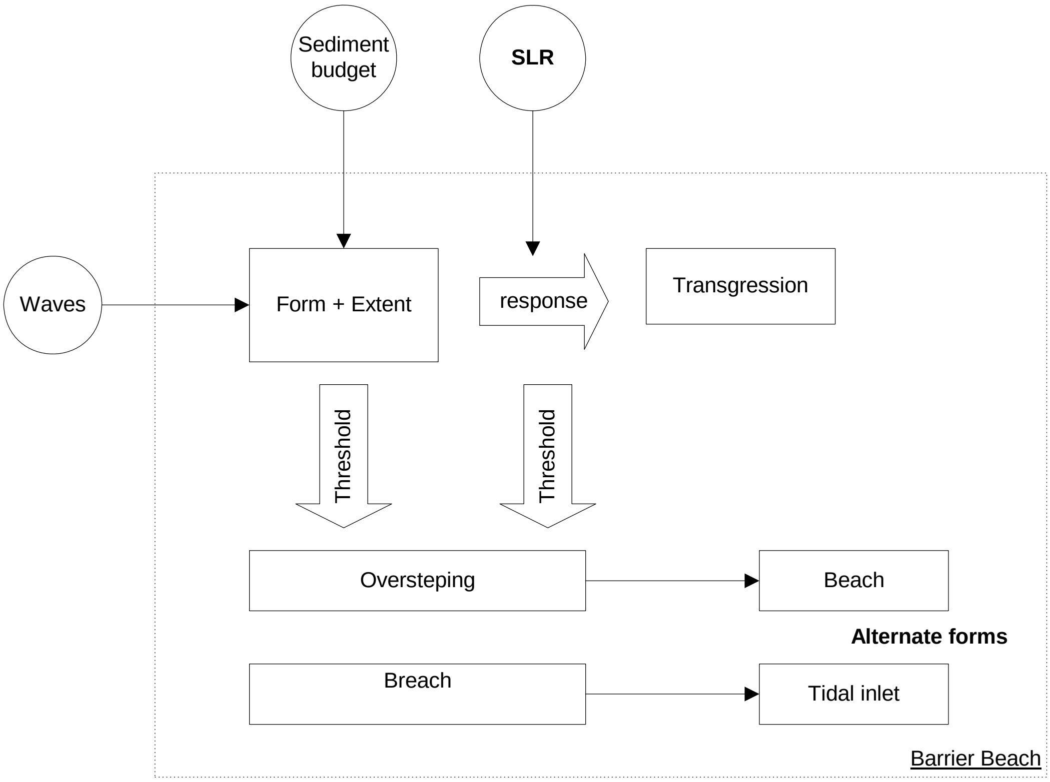
Interaction with other elements - Barrier Beach



Short to medium term system diagram - Barrier Beach



Medium to long term system diagram - Barrier Beach



Appendix C: Behavioural Description for Spits

Definition of Geomorphological Element

Spits are narrow and elongated accumulations of sand and/or gravel that project out from the coastline across part of the mouth of an estuary and, as such, are influenced by marine processes on both their seaward and landward sides. They are formed as a product of the interaction between longshore drift, moving non-cohesive sediment along the coastlines adjacent to the estuary mouth, and the tidal processes operating through the mouth. In areas where local coastal drift reversals, or 'counter drift', exists updrift of the estuary, spits can form at both sides of an estuary mouth, growing towards each other. These are referred to as double spits and classic examples can be found along many of the harbours in The Solent. Many spits are characterised by a curved termination at the distal end, caused by the wave action acting at this location.

Function

Spits can be seen to serve several functions within in the context of an estuary system. Spits represent a sedimentary interaction between the adjacent open coast and an estuary and as such their existence provides a constraint on the estuary mouth, acting as a barrier to tidal inundation, constraining the estuary channel and mouth and providing shelter to the generally intertidal areas in their lea.

Formation and Evolution

For spits to develop, there is a requirement for the along-shore coastal transportation of sand or gravel and the presence of an abrupt change in the main coastline configuration, such as caused by the presence of an estuary. As the shore-parallel littoral processes become influenced by the ingress and egress of water from the estuary, so the longshore transport rate is reduced and much sand or gravel becomes deposited at the estuary mouth. As this deposition continues, the spit will grow in length, prograding across the estuary mouth. This will continue until some critical balance is achieved between the longshore supply and deposition of sediment and the passage of tidal waters through the estuary mouth. In estuaries with relatively low volumes of tidal discharge and/or extremely high volumes of longshore drift, continued spit growth can divert the mouth of an estuary significant distances along the coast (e.g. River Adur in West Sussex) or, ultimately, lead to mouth sealing (e.g. Combe Haven, East Sussex). However, in many cases of extensive spit growth, episodes of breaching are often characteristic, thereby creating a new mouth position, followed by further periods of elongation. For example, in the hundred years leading up to the mid 1930s, Mudeford spit at the mouth of Christchurch Harbour experienced five cycles of significant progradation and breaching (Kidson, 1963). Much debate exists in the literature concerning whether double spits at estuary mouths are the result of breaching processes (e.g. Robinson 1955) or counter-drift (Kidson, 1963). Whilst breaching of a spit can provide a 'plug' of material that can be transported to the opposite side of the estuary mouth, from where an opposing spit can develop, counter-drift usually remains responsible for re-sorting this material and in most cases where double spits exist, it is most likely that some form of counter-drift is responsible for spit formation and development.

General Form

Spits can be comprised of sand and/or gravel and possess three components: a seaward face; a crest; and a landward face. In common with barrier beaches, dunes may be perched on the crest of a spit. Gravel-dominated spits will generally exhibit a steeper seaward profile gradient than their sand-dominated counterparts, whilst the crest and landward face of either sediment clast may be vegetated. Sand dominated spits tend to be flatter features. Typically, spits front low-lying sand or mudflats and saltmarshes, which are protected by the spit against wave activity.

General Behaviour

As spits are formed at locations where wave-driven littoral drift and tidal processes combine, they are usually relatively dynamic features that can be subject to changes in profile gradient, crest height, planform position and even their presence.

Considering the longshore behaviour, a spit is dependent on the balance of interactions between the littoral sediment supply and subsequent deposition, and the tidal processes operating through the estuary mouth. This can either curtail spit development to a limited length (where the tidal processes are more significant than littoral processes) or can lead to spit elongation across the estuary mouth, diversion of the mouth and even eventual mouth blockage (where the littoral processes are more significant than tidal processes). In areas where spit elongation is observed, it is often possible to identify a series of recurves within the feature, each of which marks the former end of the spit.

In a cross-shore sense, a spit generally behaves in a similar fashion to a barrier, in that tidal and wave activity tends to push material up-profile during 'normal conditions'. During slightly more extreme conditions, material may be moved so far up the profile that it becomes deposited on the spit crest, but during extreme conditions, the crest material is pushed back down the landward face, thereby causing a landward migration of the plan form position.

Episodes of temporary or permanent spit breaching can also occur, caused by either wave activity lowering the crest so that flooding occurs through the breach, or by tidal processes operating from the landward side of the spit causing destabilisation.

Over longer timescales, spits can exhibit major changes in form. Their response to rising relative sea-levels will depend on the rate of relative sea-level rise and the stability and inertia of the spit itself. Under modest rates of relative sea-level rise, a spit is likely to experience landward transgression, whereas during periods of rapid relative sea-level rise, the feature may be unable to transgress at a sufficient pace and instead break down to form a lower chenier on a sand or mud flat.

Forcing Factors

Spits generally are more common in areas of micro-meso tidal range, such as parts of eastern and southern England and west Wales (Pethick, 1984). They exist due to a combination of both wave-driven along-shore transport processes and tidal processes through the estuary mouth.

Evolutionary Constraints

Sediment supply to the spit is often important to its continued presence. This is because spits are initially formed as 'drift-aligned' features (i.e. the shoreline is oriented obliquely to the dominant wave crests so that some alongshore transport of sediment is observed along the shore). Although spits are often considered to be sinks of sediment, some material is continually removed from the spit and transported offshore, into the estuary or further along the coast, bypassing the estuary mouth within ebb tidal shoals where present. In the absence of continued supply, the spit will tend to become progressively denuded of sediment and its appearance will become progressively more segmented and 'swash aligned', caused by internal re-working of available sediments.

A constraint on the degree of spit growth, in the case of continued sediment supply, is the flushing capacity of the estuary. This flushing capacity is a balance between the rate of sediment supply along the spit, predominately controlled by wave action, and the action of tidal flows and fluvial discharge through the mouth. The action of waves driving transport along the spit will act to elongate the spit whereas the flows through the mouth will act to maintain a cross-sectional area and hence prevent spit growth in certain situations. For example, in estuaries with a very large tidal prism, it is improbable that a spit could grow sufficiently to seal or significantly divert the mouth. However, in estuaries with a small tidal prism, spit growth can commonly divert the estuary mouth, unless training works or artificial sediment recycling/bypassing activities are in place to limit this.

Behavioural Timescales

Short-term (responses within a year)
Over the short-term, spits will exhibit dynamic responses to individual 'frequent' storm events and seasonal wave climates, with processes of cross-shore and longshore sediment movement occurring and changes in profile gradient and crest height observed.

Medium-term (responses over decadal to century scale changes)
Over the medium term spit behaviour will vary according to a number of factors, for example sediment supply. Spit behaviour may involve erosion or accretion, resulting in vertical or horizontal changes in the form of the feature, and changes in the position of the feature. For example, under a scenario of relative sea-level rise, a spit may migrate landward through the process of sediment being moved from the seaward to the landward side.

In addition, spits are known in a number of cases to exhibit cyclical behaviour over these medium term timescales. This can involve a period of spit growth and elongation followed by a breach. If the breach is maintained, the sediments in the isolated section may become dispersed and the spit may begin a further stage of elongation and growth.

Long-term (responses over century to Holocene timescales)
Over the longer term, spit behaviour could cover a range of occurrences, from significant progradation, through landward migration in response to modest relative sea-level rise, to breaching or breakdown of the feature during more extreme (i.e. less frequent) storm events or rapid rates of relative sea-level rise.

Interactions with other Geomorphological Elements

General Interactions (Elements external to the estuary system)
Spits have important interactions with the adjacent shore beaches. It is from these areas that sediment is supplied to the spit.

Deltas
In some particular types of estuary, namely spit-enclosed drowned river valleys and tidal inlets, both spits and flood and ebb tidal deltas can be present. In these cases, important sediment transport pathways exist that incorporate both the spit and the deltas. A proportion of the sediments will become stored within the spit or delta features, whilst other sediments will pass through the complex pathways, episodically moving off the spit to the flood tide delta, then to the ebb tide delta and then back to temporary storage in the spit or ultimately progressing to the downdrift side of the estuary mouth and thereby bypassing the estuary.

Sandflats, mudflats and saltmarsh
Some material exchange can also occur between the spit and the adjacent sand flats within the estuary. Spits provide a degree of protection to backing sand flats, mud flats and salt marshes from direct wave attack. As the position, or presence, of the spit changes (e.g. due to landward migration, temporary or permanent breaching, breakdown of the feature), so the exposure to wave penetration of parts of the outer estuary changes. This could, for example, have the effect of causing or accelerating erosion of inter-tidal areas, or reducing the rate of accretion.

Channel
Spit behaviour will have a direct impact on an estuary or inlet mouth. The spit will exert an influence on channel dimensions at the mouth and channel dimensions will respond to any cyclic behaviour involving spit elongation and breaching. In the event of a spit breach that is maintained through tidal and wave action, the siltation is likely to be experienced in the estuary or inlet mouth (Pontee *et al*, 2002).

Dunes
Spits can become vegetated on their crests and landward slopes and in the case of particularly large sand spits, dunes can develop due to aeolian transport of sand and subsequent colonisation by vegetation.

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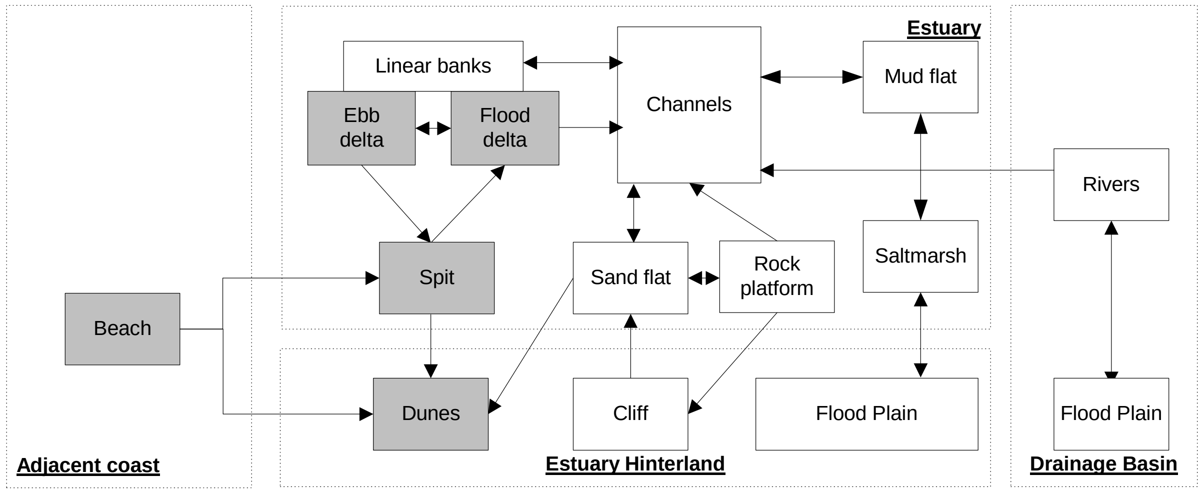
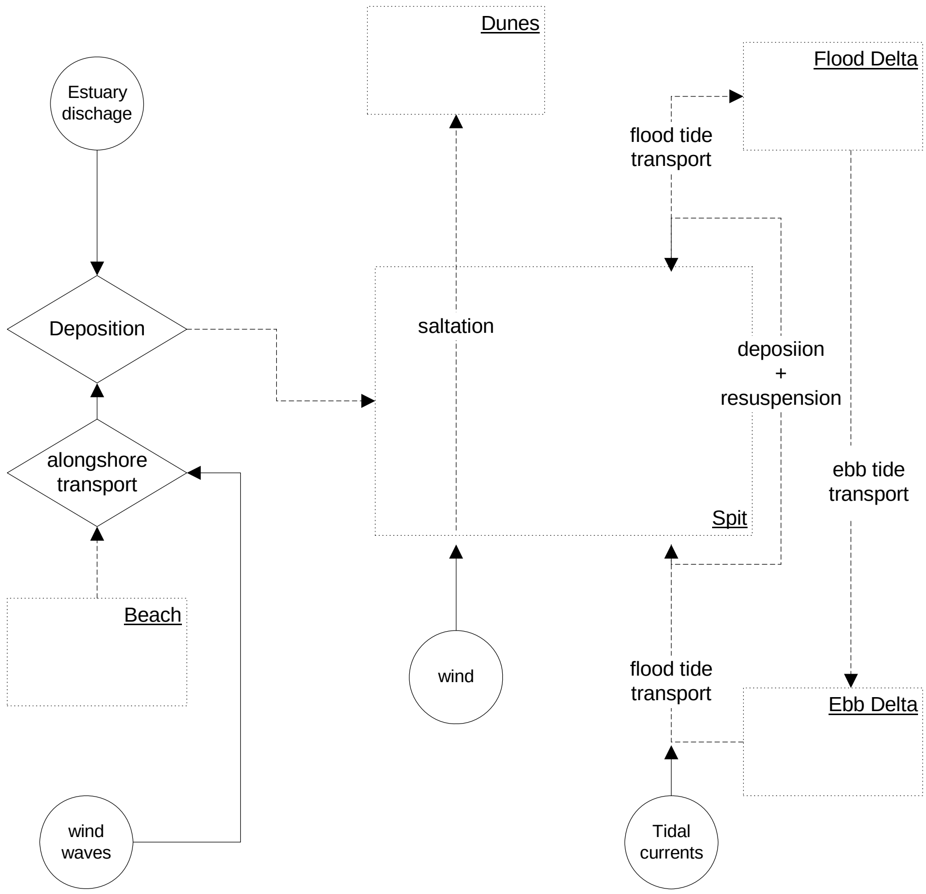
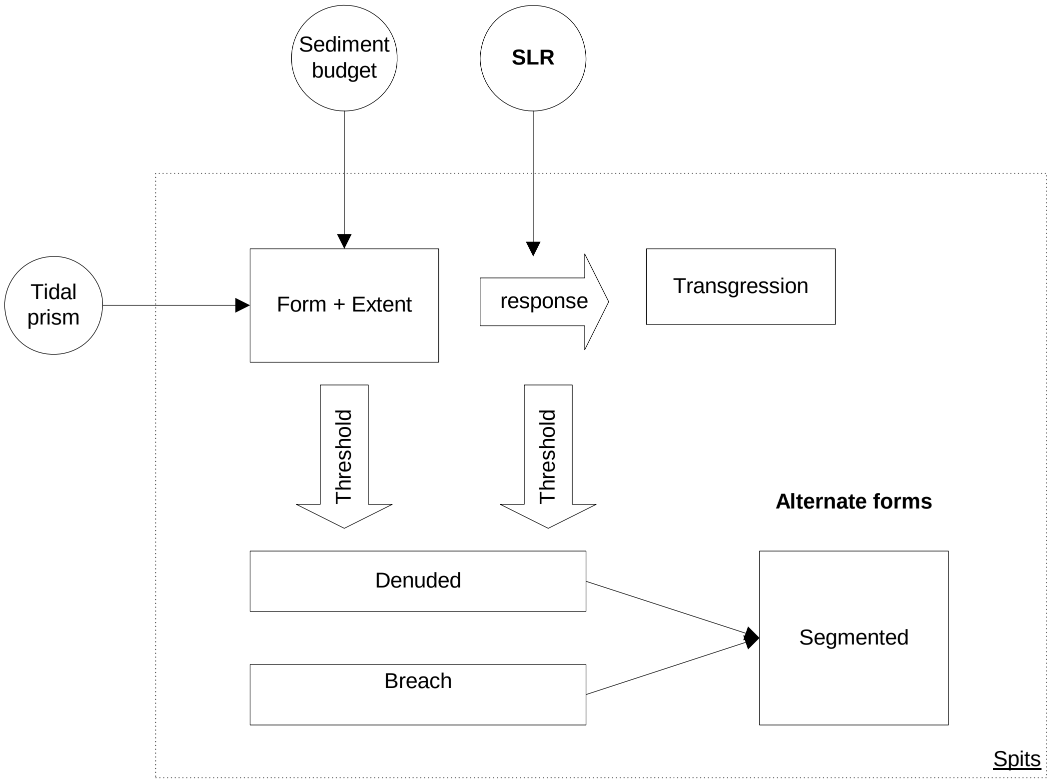
Interaction with other elements - Spits



Short to medium term system diagram - Spits



Medium to long term system diagram - Spits



Appendix D: Behavioural Description for Dune

Definition of Geomorphological Element

Coastal dunes are accumulations of sand that has been blown by the wind from the foreshore to the backshore. Such features are characterised by the presence of vegetative cover.

Function

The function of a dune system is both to provide protection to the adjacent landward hinterland and to provide a store of sediments available to the fronting foreshore. In terms of the wider coastal or estuarine system, the function is therefore fulfilled primarily during extreme events. Under such conditions, dunes provide an energy dissipation role, acting as a buffer to extreme waves and protecting the adjacent hinterland. In addition, during these extreme events, dunes provide a supply of sediment to replenish the fronting foreshore, allowing the foreshore to adapt its form.

Formation and Evolution

The wind-blown (aeolian) processes that result in dune formation are initiated when the wind stresses acting on sand particles of the foreshore exceed the shear strength of the material (which is related to sediment grain size). This process is known as saltation and particles move in this manner until their progress becomes interrupted by some obstruction, such as debris at the mark of the highest tide. Here, accumulation starts and as the mound of sand increases to form embryonic dunes, so vegetation can start to colonise. As embryonic dunes continue to accumulate sediment, they rise in height, increase in width and connect with neighbouring embryonic dunes to form more continuous ridges (often up to 2m in height) parallel to the shoreline. These ridges, due to their increased elevation, become vegetated by major dune species (e.g. marram grass). These species increase the surface roughness of the foredune and assist in the trapping of sediment, resulting in rapid deposition within the vegetated zone. This leads to rapid increases in dune height, which, in the UK, can be up to approximately 10m.

As the foredune height increases towards a self-limiting level, it will become subjected to an increasingly stronger wind velocity regime at its crest, which, eventually, will result in saltation processes moving sand landwards. On the lee side of the dune crest, the velocity regime decreases substantially, resulting in deposition and the initiation of the development of a new dune ridge. Due to the process of erosion from the crest and lee-side deposition, the entire dune ridge appears to "rollover" and move landwards (Pethick, 1984, Carter, 1988). Assuming an accretional environment prevails, as the 'roll-over' process occurs, new dunes are created seaward of the migrating ridges. This results in the creation of a series of fully developed ridges, separated by troughs or valleys.

General Form

A coastal dune field will often comprise a series of sand ridges running parallel to the shoreline, with each ridge being separated from another by marked troughs or valleys (Pethick, 1984). Other fields may have a more complex form, comprising ridges running perpendicular, or at oblique angles, to the shoreline. Typical ridge heights in the UK range from 1 or 2m to 20 or 30m and their morphology generally comprises relatively steep windward slopes and gentler lee slopes (Pethick, 1984). Each dune ridge represents a different stage in a dune field's development (Goldsmith, 1978). The crest of each ridge may be flat or undulating, but occasional areas of unvegetated low depressions (known as blow-outs) may occur.

As dune ridges migrate landwards through a succession, they eventually become lower in height and less parallel to the shoreline. This is due both to the progressive reduction in saltation that occurs with progressive movement landward through the dune field, and to the reduction or disappearance of marram grass within older dunes. As a result, the ridges become fragmented, increasingly susceptible to blow outs and, ultimately, the creation of u-shaped parabolic dunes. Parabolic dunes typically have vegetated arms orientated roughly parallel to the predominant wind direction and unvegetated centres which are subjected to downwind movement.

General Behaviour

Dune behaviour is generally linked to its stage of succession, with pioneer stages (embryonic dunes and foredunes) being typified by sand deposition to enable dune formation and growth. Intermediate stages involve the migration of dune ridges and formation of new ridges to establish dune fields, whilst the mature stages are characterised by the lowering of dune ridges, loss of vegetation cover and, due to increasing susceptibility to blow-outs, the formation of parabolic dunes. Generally, dune fields are perceived to be sediment stores, but episodically dunes can supply sediment to the fronting inter-tidal beach when wave activity is extreme.

Forcing Factors

Unlike all other coastal landforms, dunes are formed by wind-induced sediment movement rather than water-induced movement (Pethick, 1984). This involves, during periods with strong onshore wind velocities, aeolian processes transporting sand-sized sediment landward. Hence wind speed and direction is an important forcing condition in dune formation and evolution.

During periods of relatively high wave action, some of the sediment stored within the dune system can be eroded and moved seaward to feed the beach profile. This is often perceived to be a major concern to coastal management since the volumes of material involved can be relatively large, but this is a temporary state and following periods of calmer wave action, sand will once again usually move from the beach to be stored within the dunes (Carter, 1988). In addition, sediment stored within a dune system can be lost inshore.

Evolutionary Constraints

The evolution of dunes could be constrained by either a reduction in sediment supply or the lack of accommodation space to enable dune succession.

Behavioural Timescales

Short-term (responses within a year)
In the short-term, dune behaviour can be extremely dynamic, with significant sediment accumulation or significant local sediment loss, due to blow-outs or erosion of the seaward margins, both possible outcomes.

Medium-term (responses over decadal to century scale changes)
Dune behaviour over medium timescales will consist of changes in the position and nature of a dune system. Depending on the degree of landward space and the sediment supply, a dune system may 'roll-over' landward in response to an increase in relative sea-level. Conversely, under a scenario of falling relative sea-level a dune system may prograde seaward, under a scenario of sufficient sediment supply.

Long-term (responses over century to Holocene timescales)
Over longer-time periods entire dune fields can develop, containing a series of ridges created during different stages of its evolution. Over similar timescales, entire dune fields may also be lost due to erosion or inundation or alternatively a dune system may stabilize or become a relict feature. The change in relative sea-level is the critical controlling factor in the behaviour of dune systems over this timescale. In addition, the supply of sediment will determine the nature of the features response the prevailing relative changes in relative sea-level.

Interactions with other Geomorphological Elements

General Interactions (Elements within estuary system)
The key interaction is between the dune and the fronting inter-tidal foreshore. Sand is supplied to the dune from the foreshore by aeolian processes, but can also be temporarily supplied from the dune to the fronting foreshore during extreme events.

Dunes can also develop on the crest of major spit or barrier features; with Spurn Head being a classic example. In such situations, it is possible that a marsh system may develop in the lee of the dunes, to which the dune system provides protection.

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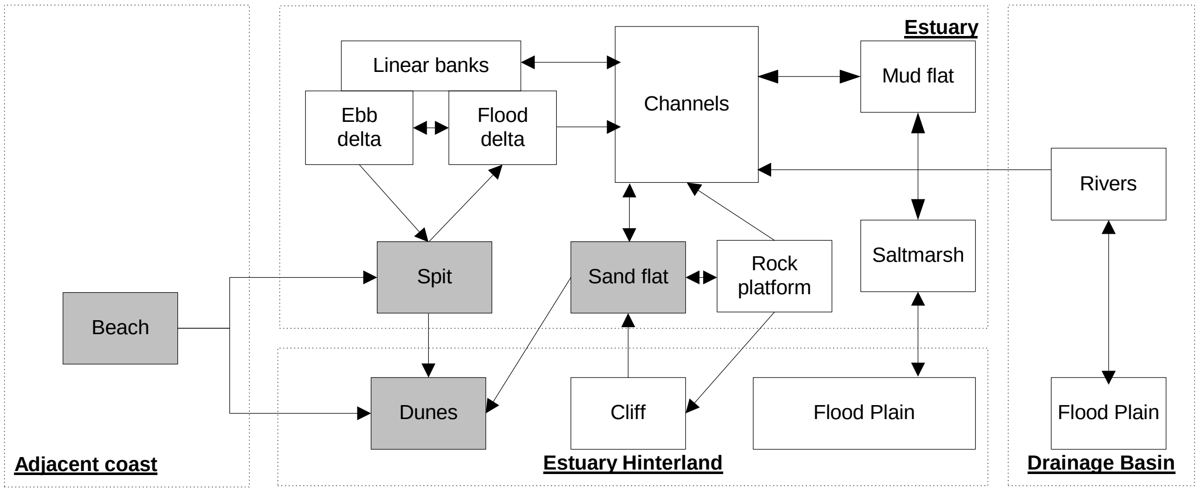
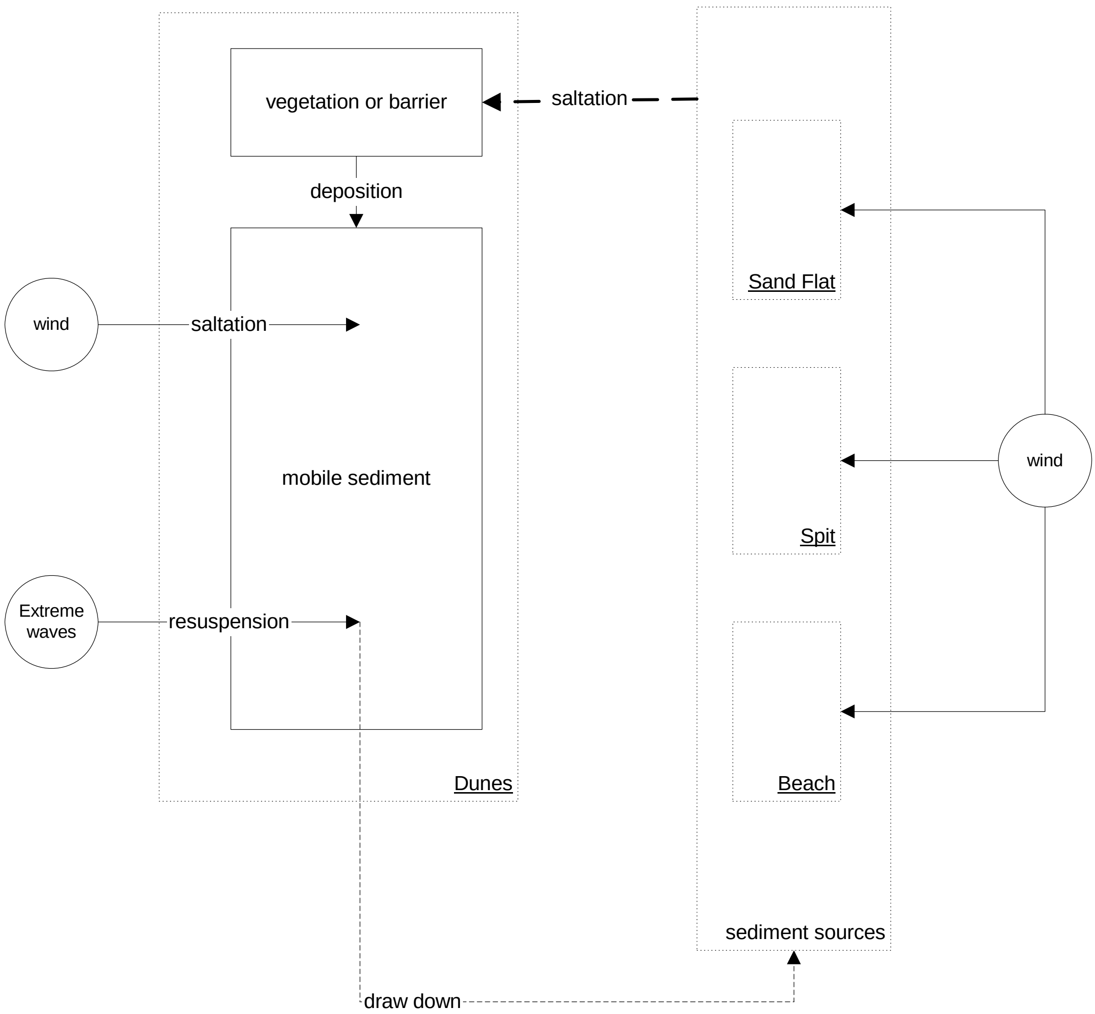
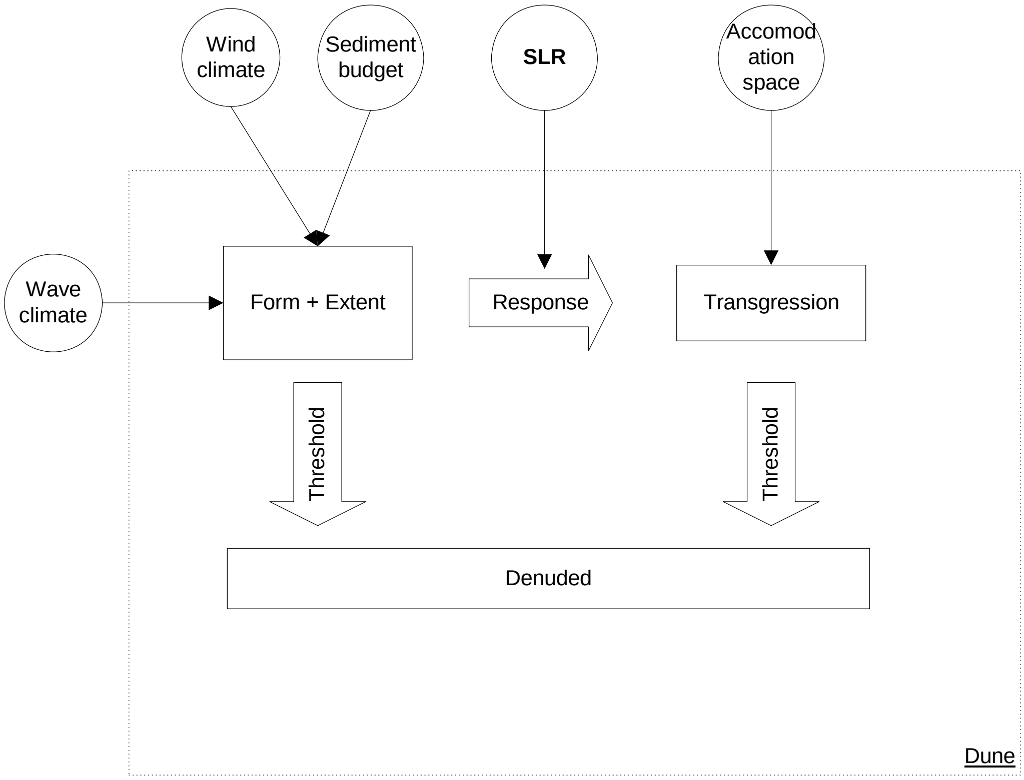
Interaction with other elements - Dunes



Short to medium term system diagram - Dunes



Medium to long term system diagram - Dunes



Appendix E: Behavioural Description for Delta

Definition of Geomorphological Element

Deltas can be defined as accumulations of river- or marine-bourne sediment found in the vicinity of the estuary mouth. Their existence is dependant upon a sufficient supply of material and favourable wave and tidal conditions. Deltas can exist as flood or ebb features. For the purpose of this study the occurrence of linear sand banks within an estuary mouth is considered as a modified delta with littoral supplied sediment to the mouth of an estuary incorporated into elongated sand accumulations aligned with the current flow.

Function

Within the estuarine system, deltas act to dissipate wave energy at the estuary mouth thus providing protection. In addition, they also act as a sediment sink. Under certain conditions the delta will also act as a sediment source i.e. when the wave characteristics provide sufficient energy to suspend bed material. A delta represents a sedimentary interaction between the estuary and the coastline to either side of the estuary mouth.

Formation and Evolution

If more sediment is supplied to an estuary mouth or tidal inlet than can be redistributed by the dominant processes, then a delta will be formed. Conversely if the waves and currents can remove more sediment than is being delivered to the estuary mouth, then the delta retreats or the sediment load is incorporated directly into the beach or within an estuary and delta is not formed.

There are therefore two generalized situations in which delta formation will occur:

- If the fluvial sediment supply exceeds the flushing capacity of processes at the estuary mouth;
- When wave driven longshore transport supplying sediments to an estuary mouth from an adjacent coastline is interrupted by the interaction of wave and tidal processes at the mouth.

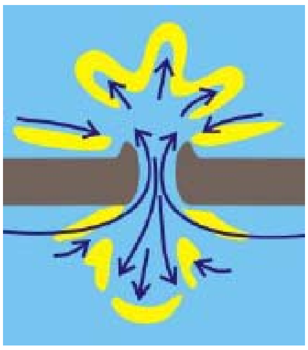


Figure E1. Schematic Illustration of Delta Formation Processes at a Tidal Inlet/ Estuary Mouth

General Form

Deltas can be classified according to the relative importance of fluvial, tide and wave processes in their formation. The relative importance of these processes will play a role in dictating the form of the Delta. Van Rijn (1998) classified three distinct types of Deltas, as follows:

- River-dominated deltas form where rivers supply a sufficiently large sediment load to overwhelm the rate of marine-induced re-working and removal. They are often comprised of numerous branching river distributory channels and the presence of lobes. These deltas tend to be long narrow features;

- Wave-dominated deltas form where river- or coastal-bourne sediment is sorted and transported from the estuary mouth in both longshore directions by waves. Such sediment is often transported to features such as beaches, barriers and spits. Typically such deltas are wide features with multiple outlets; and

- Tidally dominated deltas form in meso-tidal estuaries where the tidal conditions are sufficient to transport sediment to the estuary mouth. Such deltas tend to comprise ebb delta located seaward of the estuary mouth or tidal inlet and flood delta located inside the estuary mouth or tidal inlet.

  A modified delta may form in macro tidal estuaries as linear sand banks with sand accumulations aligned parallel to the flow.

General Behaviour

Delta behaviour is complex and results from a combination of the relative dominance of the driving processes (fluvial, wave and tidal processes) and the supply of sediment. Whilst tidal processes play the predominant role in the formation of the tidal delta, wave-generated processes are also important, tending to supply the coarser material to the flood tidal delta. Often finer materials are progressively removed from the flood tidal delta resulting in an eventual differential between the adjacent updrift and downdrift beaches. However, fine sediments may also be transported from the flood delta to the ebb delta and subsequently feed the downdrift coastline.

Forcing Factors

At the mouth of an estuary three processes will contribute to delta formation and the distribution of sediments (Futurecoast, 2002):

- Inertia-dominated material: The inertia created by high velocity outflow results in the material spreading and diffusing as a turbulent jet. The expansion of this jet reduces its velocity resulting in a reduction of its sediment carrying capacity. The sediments are deposited in a radial pattern, with the coarsest material deposited near to the point where the jet expansion begins and the finer material further afield. With the continual discharge of sediment, the delta will accrete vertically and eventually have a frictional effect on the material;

- Friction-dominated material: The continual deposition of sediment from the turbulent jet will eventually cause the restriction of the jet. This in turn will result in the formation of bars and channels;

- Buoyancy-dominated material: The mix of fresh and saline water often results in stratification, which in turn initially results in the material being isolated from bottom friction effects. Consequently, the sediment will be distributed over a wide area until the upward entrainment of seawater across the density interface results in its deceleration and settlement.

Within tidally dominated estuaries, tidal interaction has three important effects:

- At estuary mouths, mixing obliterates the effect of vertical density stratification thus eliminating the effects of buoyancy;
- Tide-dominated sediment transport is bi-directional; and
- The zone of fluvial-marine interactions extends across a wider area.

Evolutionary Constraints

The evolution of a delta may be constrained by a number of factors, such as:

- Sediment supply (including the source and nature of sediments and the rate of supply);
- River, wave and tidal processes, and their interaction at an estuary mouth;
- Coastal alignment and nearshore bathymetry (including the configuration of the adjacent coastline, the position and nature of the estuary mouth, the behaviour of adjacent spits etc.).

Behavioural Timescales

Short-term (responses within a year)
In the short-term, delta behaviour will be dominated by changes in size and form and migration of the feature. This behaviour will be in response to variations in forcing processes of river flows, waves and tides resulting in variations in exposure and sediment supply.

Medium-term (responses over decadal to century scale changes)
Over the medium term, even if the tidal inlet as a whole is in dynamic equilibrium with the forcing factors, appreciable local changes in morphology can be observed. These may lead to the spatial relocation of the complete inlet system, or just components within it. Examples of such local changes are the shoal-channel cycles, which for the Wadden Sea inlets have cycle periods of many decades (de Swart, 2002).

Long-term (responses over century to Holocene timescales)
Over longer-time periods, delta behaviour will be linked to the behaviour of the estuary mouth in response to changes in relative sea-level and variations in sediment supply.

While the gross morphological changes of outer deltas may be determined by global processes forcing these changes such as relative sea-level rise or a gradual decrease of the basin area, it is expected that the local, (quasi-) rhythmic changes of outer deltas are determined by processes intrinsic to the outer delta. This so-called free behaviour is hypothesised to be driven by subtle, second-order effects embedded in the first-order signal of intra-tidal and intra-event fluxes of water and sediment interacting with the bottom evolution (de Swart, 2002).

Interactions with other Geomorphological Elements

The interactions of deltas with other geomorphological elements have been investigated to varying degrees. Typically the ebb tidal delta has been the focus of much of this work, especially along US coast and within the Wadden Sea (van der Vegt *et al*., 2004). In most recent years this work has taken the focus of modelling the interactions, behaviour and evolution of such features over varying timescales. An example is that of the ASMITA model which has recently been developed from a one element to a three element numerical scheme (Stive, 2003).

Deltas are ultimately dependent upon the presence of a river or estuary and the supply of sediment from:

- Rivers (via channel system); and/or
- Longshore transport from shoreline sources (spits); and/or
- Onshore transport from the eroding seabed.

General Interactions (Elements external to the estuary system)
Essentially, deltas play an important role in the exchange of material between the coastal zone and estuary (or backwater basin) (cf. van Leeuwen *et al*., 2003). There is therefore an important sedimentary interaction between a delta and adjacent coastlines.

These features often provide considerable natural protection to the coastline adjacent to estuary mouths (Dyer & Huntley, 1999). Reductions in the delta volume, sediment supply or reclamation within the estuary, will lead to reduced natural protection to adjacent shorelines and, hence, increase their susceptibility to erosion.

The response of a tidal delta (in terms of volumetric reduction) to such anthropogenic changes can be very significant, but is not instantaneous. Instead, due to the inherent time lags within the coastal system, it can take decades or centuries of slow progressive ebb-delta modification to fully respond to such interventions.

Deltas/linear banks act as large sediment stores. Whilst this material tends to remain within the bank temporarily, it may, due to changes in forcing factors, be released to re-enter the sediment transport pathway. This could be either in the longshore, onshore or offshore directions. It is likely that this behaviour will be over a short- to medium-term period, rather than the long-term, whilst the bank responds to changing conditions to re-attain equilibrium.

Perhaps the more significant interaction that the banks have with other elements within the local system is with the immediate shoreline. Here banks refract incoming waves influencing wave energy at the shoreline. In turn this will control shoreline evolution and, subsequently, backshore features in response to wave processes.

Spits/Barrier Beaches

The above 'general interactions' discussion focuses on the link between deltas and the adjacent coastline. This interaction equally applies to spits and barrier beaches. A strong linkage exists between spit/barrier beach behaviour and delta behaviour, with cycles of spit/barrier growth and breaching affecting the location and nature of the estuary mouth or tidal inlet and hence the behaviour of any delta associated with the mouth.

Deltas and spits/barriers therefore often provide the sediment linkage between an estuary and adjacent coastlines.

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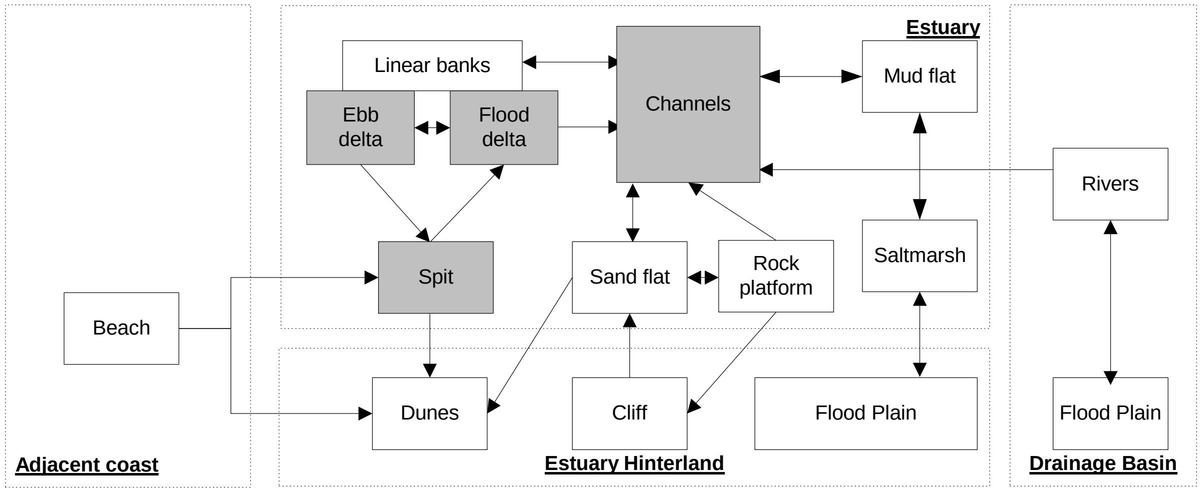
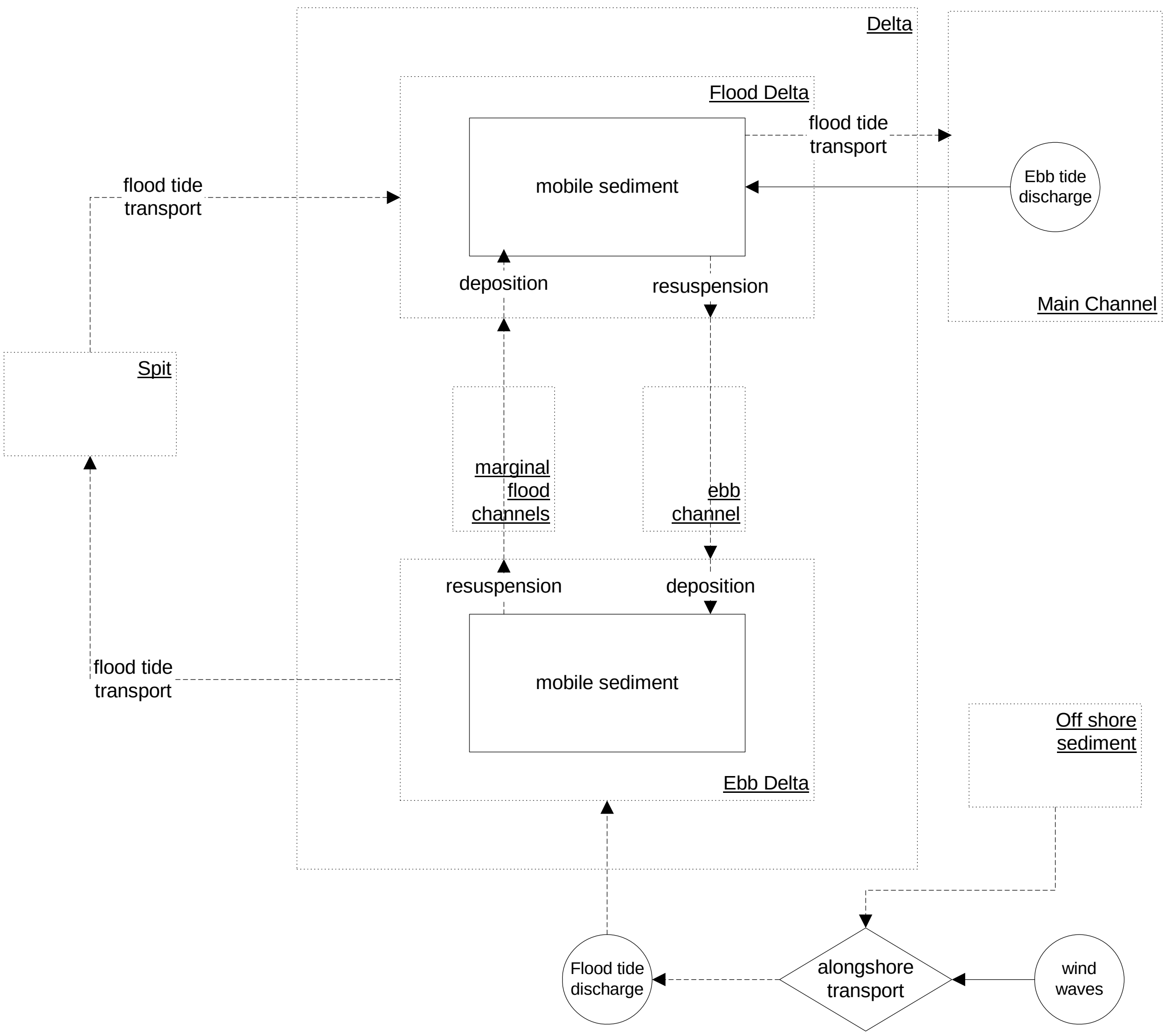
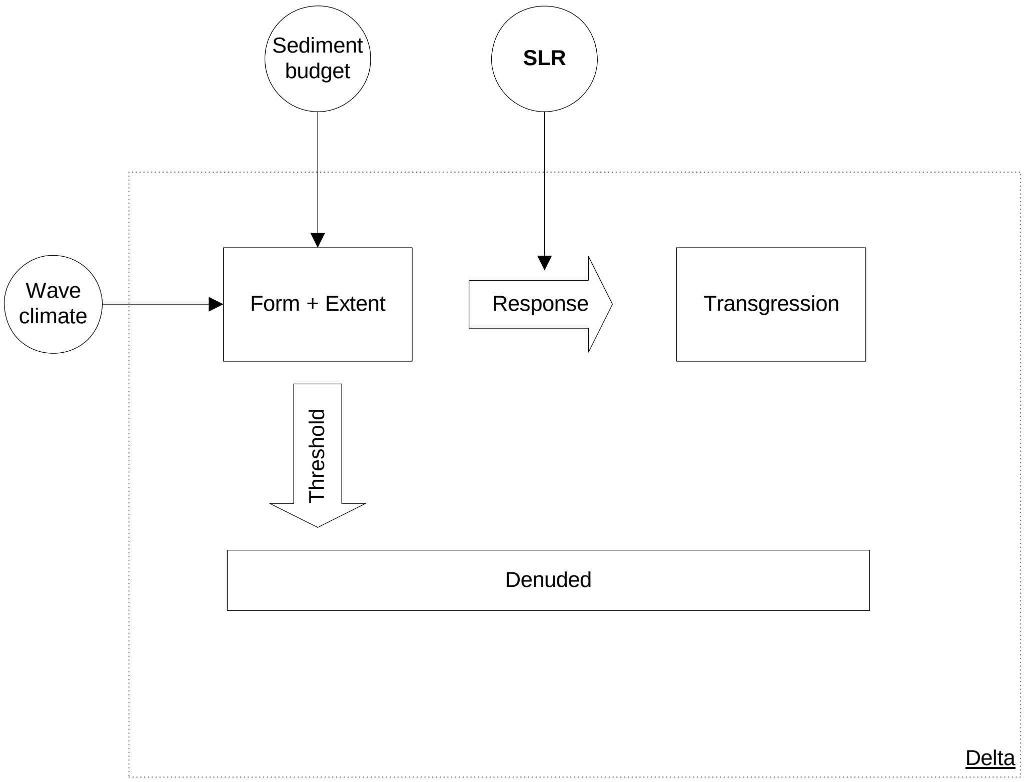
Interaction with other elements - Delta



Short to medium term system diagram - Delta



Medium to long term system diagram - Delta



Appendix F: Behavioural Description for Rock Platform

Definition of Geomorphological Element

Rock platforms are defined as relatively flat erosional rock bench bedforms extending across, and sometimes seaward of, the inter-tidal zone (Carter, 1988). It is important to note that they are affected not only by marine processes (such as mechanical wave erosion or abrasion by mobile non-cohesive sediments) but also by sub-aerial, chemical and biological processes that can serve to weaken the rock structure.

Function

The function of a rock platform is to reduce wave and tidal energy before it reaches the upper inter-tidal zone. Additionally, as rock platforms erode (lower), so they: (i) control the rate of recession of backing cliffs; and (ii) release sediment, some of which can contribute to the littoral sediment budget (coarser material) and/or some of which can be transported in suspension offshore or into estuaries (finer material).

Formation and Evolution

Rock platforms are often backed by sea cliffs and the lithology and geotechnical properties of the two are often closely related. Similarly to cliff evolution always being recessional (albeit at varying rates dependent on the rock geology), so shore platforms will not experience regression (seaward or vertical advance of the landform) since they represent a finite feature that can only become progressively more denuded. Consequently any erosion (lowering) that they experience is irreversible.

Shore platform lowering is initiated when the stresses acting on the feature exceed the shear strength of the material. This situation may arise due to a combination of a number of factors. In basic terms, these comprise external factors that may exist or occur which increase the shear stresses applied or internal factors that may exist or arise which result in a decrease in the shear strength of the material.

An example of the typical foreshore lowering rates of rock platforms comprised of rocks of different lithology is presented in Table F1.

Table F1. Typical lowering rates of platforms composed of different materials (Sunamura, 1983)

Cliff Composition	Typical Recession Rate (mm per year)
Granite	< 0.1
Limestone	0.1 to 1
Shales	1 to 10
Firm sandstone, mudstone	1 to 100

In depositional environments, beach sediments may sit on top of a shore platform and protect it (to some degree) against erosion, although such deposits are very mobile and, consequently, usually would only remain in-situ temporarily. Indeed, as they move across the platform, they can contribute to lowering processes through abrasion. In erosional environments, shore platforms would usually be bare of superficial sediment cover and subjected to slow rate, progressive lowering due to erosional forces.

Pethick (1984) identified that the presence or absence of a (semi-) protective sediment covering on the platform was not a simple relationship, but involved a feedback mechanism whereby a lowering of the shore platform would raise the effective depth of water. Hence, the platform would be subjected to reduced bed shear stress due to waves, with resulting values possibly being lower than the critical shear stress for erosion, at which point superficial sediments may once again begin to cover the shore platform.

General Form

Burd (1968) identified three generic types of shore platform:

- Horizontal surface lying at high tide level;
- Horizontal surface lying at low tide level; and
- Sloping surface between high and low tide levels.

Despite the above classifications, Trenhaile (1978) identified that the mean elevation of shore platforms from around the world clustered around the mid tide level.

Shore platforms around the UK generally are gently sloping or quasi-horizontal in profile and variable in width, up to a maximum limit of 1km (Pethick, 1984).

General Behaviour

In general terms, shore platform evolution displays a number of important components. Certain processes will lead to the detachment of clasts of material from the platform, which will then be transported by nearshore currents, often in a landward direction. These materials will then be deposited, often on the foreshore, where they constitute valuable sediment input to the beach material stock. Ultimately, these processes lead to a noticeable lowering of the elevation of the platform over time.

As previously stated, shore platform behaviour can only involve erosion, leading to lowering. The rate of lowering will depend upon a number of factors, which may: promote the erosion of clasts of material from the platform; and control the rate and direction of transport of the released material.

In broad terms, these factors can be influenced by the hardness, structure (e.g. faulting) and solubility of the rock, biological processes and the exposure of the platform to wave attack.

Forcing Factors

The primary external cause of shore platform lowering is wave action, which may have the following impacts:

- Quarrying of rock by mechanical hammering, shock or air compression;
- Generating the oscillatory movement of abrasive particles across the shore platform, resulting in its denudation;

- Determining the subsequent transport of released material (i.e. moving sediments that potentially could provide a (semi-) protective covering away from the platform, re-exposing it to direct wave attack).

In addition to this, internal factors may result in a decrease in the shear strength of the material of which a shore platform is comprised, making the rock surfaces more susceptible to erosion by wave action. Mechanical, sub-aerial, chemical or biological weathering could cause such effects. For example, the alternating wetting and drying of the platform due to tidal movements results in water-layer weathering. This may involve physical rock breakdown caused by salt crystallisation or swelling of rock grains.

The fate (rate and direction of transport) of sediment released from platform lowering is dependent upon its composition, the direction and magnitude of the forces to which it is subjected.

Evolutionary Constraints

Unlike many coastal landforms, shore platforms will only experience lowering over time since they constitute a finite feature, which is progressively subjected to erosion, leading to lowering.

At the most fundamental level, shore platform behaviour is dependent on:

- The strength of the material in the platform;
- The stresses applied to the platform; and
- The direction of transport of released material.

Behavioural Timescales

Short-term (responses within a year)
In the short-term, platforms will be subjected to erosion at locations where the rock has been weakened during periods of higher than usual wave and/or tidal energy exposure. This will release clasts of sediment from the platform that will subsequently be transported by the forcing conditions.

Medium-term (responses over decadal to century scale changes)
In the medium-term, behaviour is manifested though a general lowering of the entire platform.

Long-term (responses over century to Holocene timescales)
Over longer timescales, platform behaviour will be dominated by changes in relative sea-level, affecting the elevation of a platform relative to water levels and hence exposure to erosive processes.

Interactions with other Geomorphological Elements

Cliffs
Hutchinson (1986) suggested that the rate of platform lowering controls sea cliff recession in the following way:

Rate of sea cliff recession = Rate of platform lowering/shore platform gradient

The implications of this relationship are that, irrespective of platform gradient, a lowering platform has direct implications for the degree of cliff recession. Both of these aspects in turn have implications on the volume (and type) of material that is released through erosion and becomes available to contribute to the littoral sediment budget (coarse sediments) and provide input to estuaries (fine sediment).

The rate of platform lowering can be reduced when a (usually temporary) veneer of sediment covers the platform (although this can actually also lead to increased erosion due to abrasion when the veneer is very thin and mobile).

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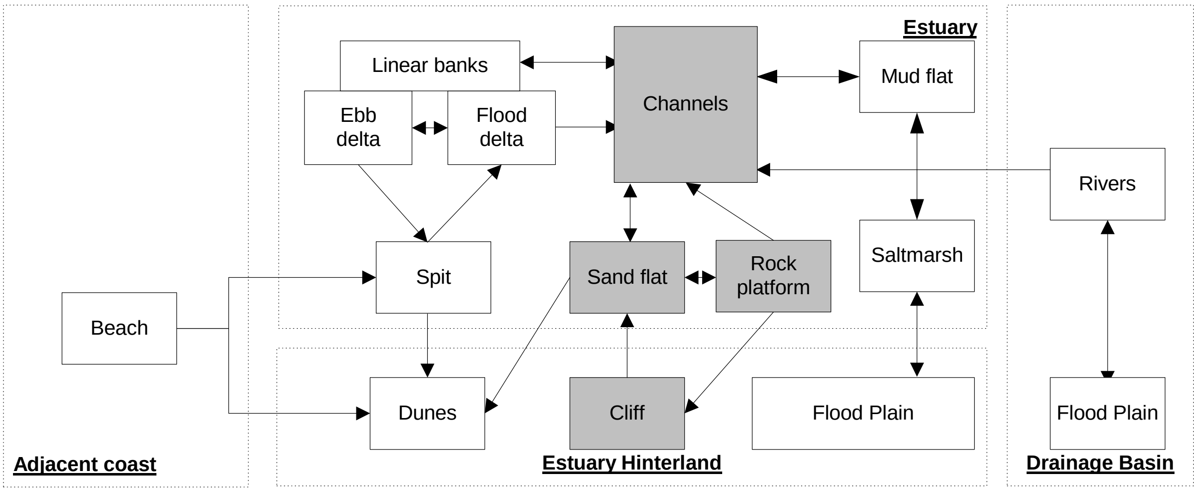
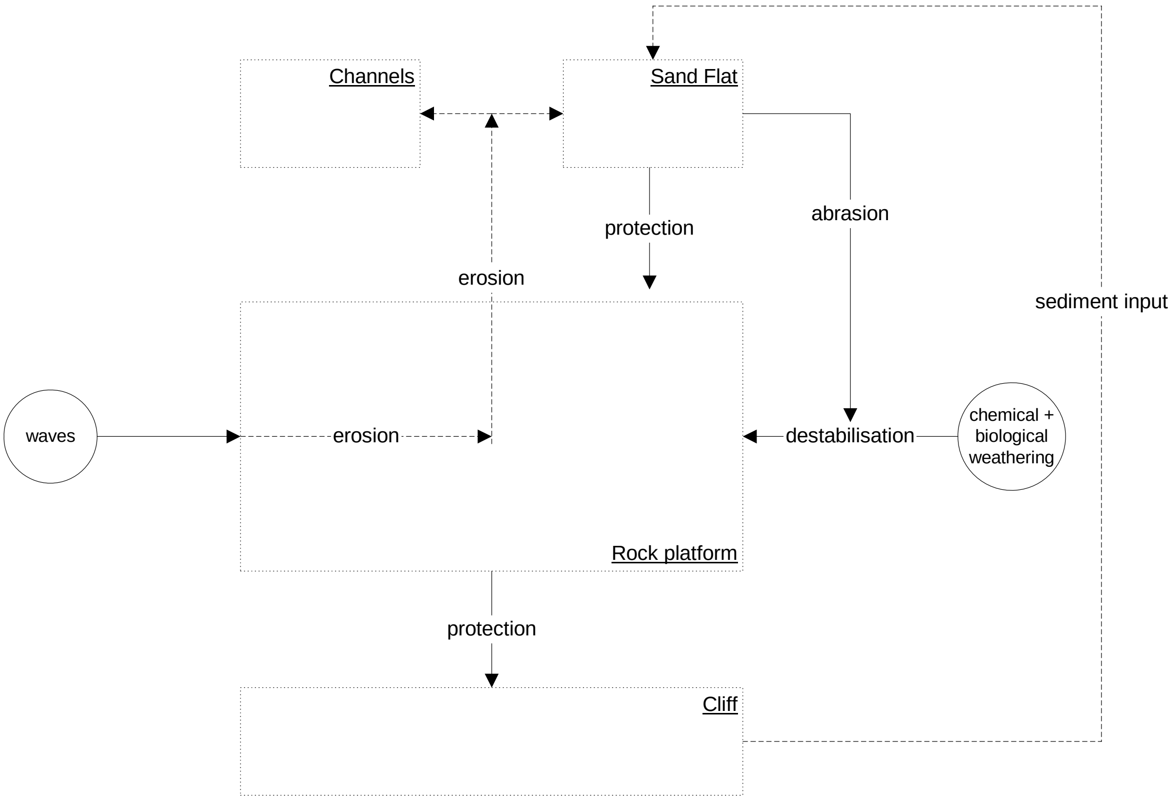
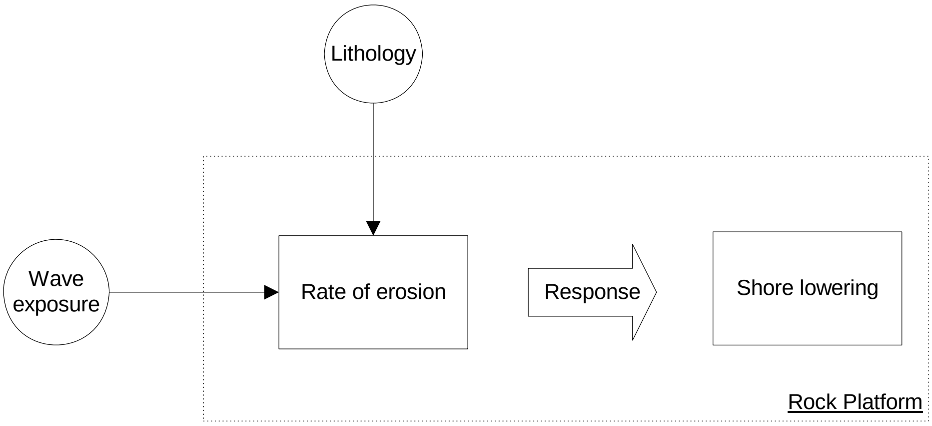
Interaction with other elements - Rock Platform



Short to medium term system diagram - Rock Platform



Medium to long term system diagram - Rock Platform



Appendix G: Behavioural Description for Channels

Definition of Geomorphological Element

Channels can be defined as sub-tidal morphological elements within the estuary bed, which are deeper than the surrounding deltas, banks or tidal flat features. The existence of these features is dependant upon favourable sediment and tidal conditions and can be present as a flood, ebb or main feature.

Function

The main function of channel is the discharge of fluvial flows through the estuary to the marine environment. Channels also allow for the tidal exchange of saline waters. As such the channel therefore allows the transmission of energy and sediment throughout the estuary and in doing so provides the link between many of the geomorphic elements within the system.

Formation and Evolution

The nature of the main channel will be dependant upon antecedent conditions and the degree of Holocene infilling with wave climate and tidal processes providing contemporary physical controls. The evolution of a main estuary channel is intrinsically coupled with evolution of the whole estuary form. A morphological concept that attempts to describe this evolution is based on the application of regime theory.

Regime theory describes an approach to channel theory that assumes some form of equilibrium relationship between certain morphological parameters, such as width, or depth and hydraulic parameters such as hydraulic slope, discharge, or flow velocity. A summary of the range of relationships available has been drawn together by Spearman and these are briefly summarised in (Spearman, 1995) and ABPmer Estuaries Morphological Guide (ABPmer, 2004). In its simplest form the relationship dictates that cross sectional area of a channel will adjust to changes in flows and *Vic versa* in order to attain equilibrium.

An alternative model of estuary and channel evolution is associated with tidal asymmetry (Pethick, 1994). In this model, tidal propagation within a wide deep channel results in a flood dominance and potential net import of sediment and accumulation on intertidal areas. As this change progresses, the morphological form evolves towards a central 'slot' channel with reduction in flood dominance and ebb dominance prevailing resulting in a potential export of sediment. Thus a morphological equilibrium is attained between the two channel types (See Figure G1, below)

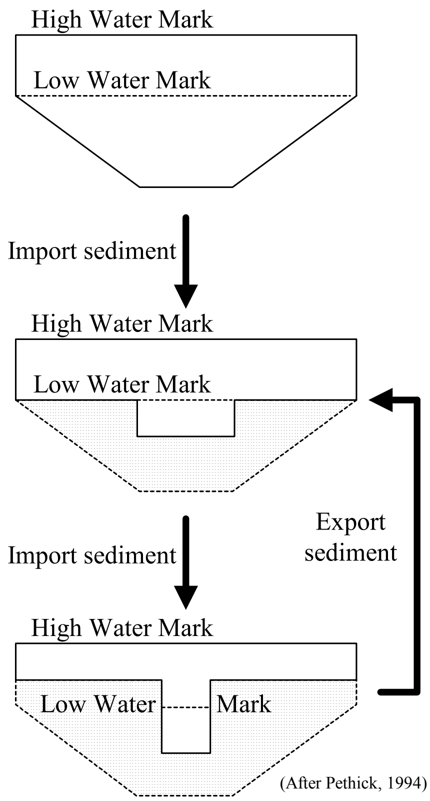


Figure G1. Stages of Estuary Development (Pethick, 1994)

General Form

The general form of channels is highly variable and site specific. The principle forms of channel can be identified according to their function. Feeder channels exist linking the catchment basin to the main channel and the main channel provides the principle conduit for energy and sediment exchanges in the estuary. In certain cases, flood and ebb flow separation can occur, with peak velocities occurring in different channel at different stages of the tide. In large estuaries, the Coriolis force (due to the earth's rotation) can be an important factor in flow separation and the development of flood and ebb channels. In plan form, channels can vary form predominately straight, to meandering and braided. This form is related to channel length, gradient and energy distribution.

General Behaviour

Channels have a range of behavioural responses to different forcing (van Rijn, 1998):

- **Meandering**. This behavioural response involves changes in the channel curvature due to erosion and accretion patterns along the channel edge. Depths will be greater and of a steeper gradient on the outside of the curve and shallower and of a gentler gradient on the inside. Meandering is an important characteristic found in the inner, or landward, sections of a number of estuaries. Meander formation in estuarine channels is complex, relative to fluvial channels, due to the presence of bi-directional flows and the mixing of saline and freshwater. Meander wavelengths in estuaries are related to tidal discharge and freshwater flows, with estuarine wavelengths greater than river wavelengths. Meandering in estuaries can be associated with mid channel shoals, either with switching occurring involving the migration of the channel from one to the other side of the shoal or flow separation either side of the shoal

- **Lateral shift/channel switching**. A consequence of sediment erosion along the channel edges. This occurs in the direction of the net cross-channel sediment flux. Sediment eroded from the bars and shoals is transported into the channel and result in a reduction of the cross-sectional channel area. As a result of the systems need to return to equilibrium, currents will act to erode the channel sides resulting in a net shift of the channel. Channel instability of this nature is a process related to meandering and can be an important process in certain estuaries. This process can result in progressive lateral shifting of the channel, as defined by the movement of the thalweg, or sudden channel switching. The precise causes of catastrophic channel switching are likely to be estuary specific. However, at a generic level a number of triggers can be identified, such as high freshwater flows (above a critical threshold level and coincident with a certain tidal state) and antecedent conditions. Channel switching has been noted as an important process in a number of UK estuaries, notably including the Humber (Pontee *et al*, 2004).
- **Widening and narrowing**. Changes in the channel form due to variations in the tidal volume passing through the channel.
- **Rotation**. A larger scale lateral shift can occur at the channel mouth. This can be a consequence of changing wave action or other forcing which acts to cause deposition on the updrift side and eroded on the downdrift side of the estuary. This change will be accompanied by channels on the ebb delta.
- **Length change**. This is a consequence of the currents cutting into a bar or shoal. This process results in an increase in channel length. Length changes may also occur due to channel infilling. This may result in a channel becoming incised or alternatively may cause an increase in channel sinuosity thereby increasing the channel length.

Forcing Factors

Physical processes within a channel are essentially dependant upon the gross properties of the estuary within which the channel is a component, including:

- Tidal Range;
- Wave climate;
- River discharge;
- Channel scale (width and depth and cross sectional area); and
- Sediment availability and composition.

The interaction of these influences with the morphological form determine the specific internal characteristics and behaviour, including:

- Energy dissipation and speed of tidal propagation;
- Tidal asymmetry and ability for net import and export of sediment; and
- Degree of mixing (longitudinally and laterally) between saline and freshwater (and effect on sediment transport through residual currents, position of turbidity maximum and flocculation).

General Behaviour

The behaviour of a channel will in part be a function of its location within the estuarine system. Upstream channels associated with the transitionary zone between fluvial and fully estuarine conditions will have a form dependant to a greater degree from fluvial discharges, where as the form of a main channel of an estuary co-adjusts with physical processes.

Behavioural Timescales

Short-term (responses within a year)
Over the short term channel behaviour will be influenced by episodic events, such as fluvial flood events. These events can act as triggers to channel switching.

Medium-term (responses over decadal to century scale changes)
Over the medium term, channels will also undergo a morphological adjustment to sea-level rise. This response occurs over a long temporal period, but is ultimately dependant upon the rate of sediment supply and relative sea-level change. Two examples have been taken from van Rijn (1998):

(1) Relatively rapid sea-level rise

- Sediment supply is insufficient therefore the channels are unable to respond;
- The tidal channel volume will increase, in turn leading to an increased tidal prism;
- Whilst the channels will undergo some siltation, this will be more than balanced by increased channel dimension in order to accommodate for the increased tidal prism; and
- Channels within the outer delta will increase.

(2) Relatively slow sea-level rise

- Sediment supply is sufficient to allow the channels to respond;
- Tidal channel volume, and thus tidal prism, remain constant; and
- Equilibrium is maintained, as the sediment supply and demand balance remains constant. However, if supply were to outmatch demand, deposition will occur. This may ultimately lead to a decrease in the tidal prism and estuary closure.

Long-term (responses over century to Holocene timescales)
Over the longer term, the development of the channel will be linked to the evolution of the overall estuary form. The channel is likely to widen or narrow and lengthen or shorten as the estuary translates in position in response to relative changes in relative sea-level.

Interactions with other Geomorphological Elements

General Interactions (elements within the estuarine system)
Whilst the responses of the channels have been described above in the context of sea-level rise, the changes that occur will be intrinsically linked to other features within the estuarine system. Indeed any changes to the form and behaviour of channels will be observed in corresponding changes to, primarily, the intertidal area (saltmarsh and mudflat), deltas and banks and spits.

This process occurs as the migration of channels allows the release of sediment surrounding geomorphic elements e.g. sand and mudflats, saltmarshes, dunes, spits, etc. This sediment is then available to be reworked by the prevailing processes and deposited elsewhere to contribute to these existing geomorphic elements or form new versions of the pre-existing elements.

In addition to this direct impact on features from channel migration, the movement of the channel may also impact on adjacent features through changes to the degree of exposure to wave and tidal action.

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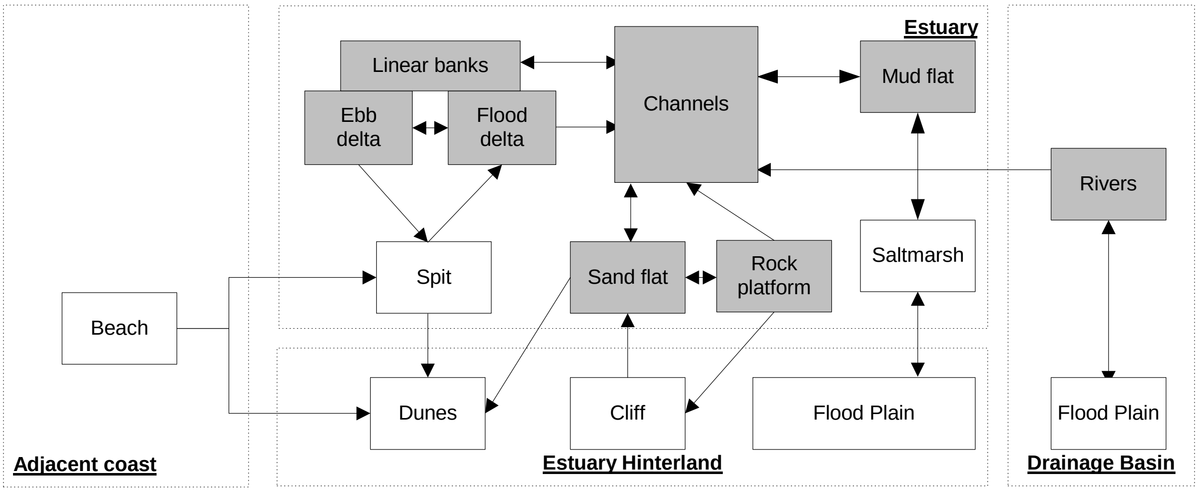
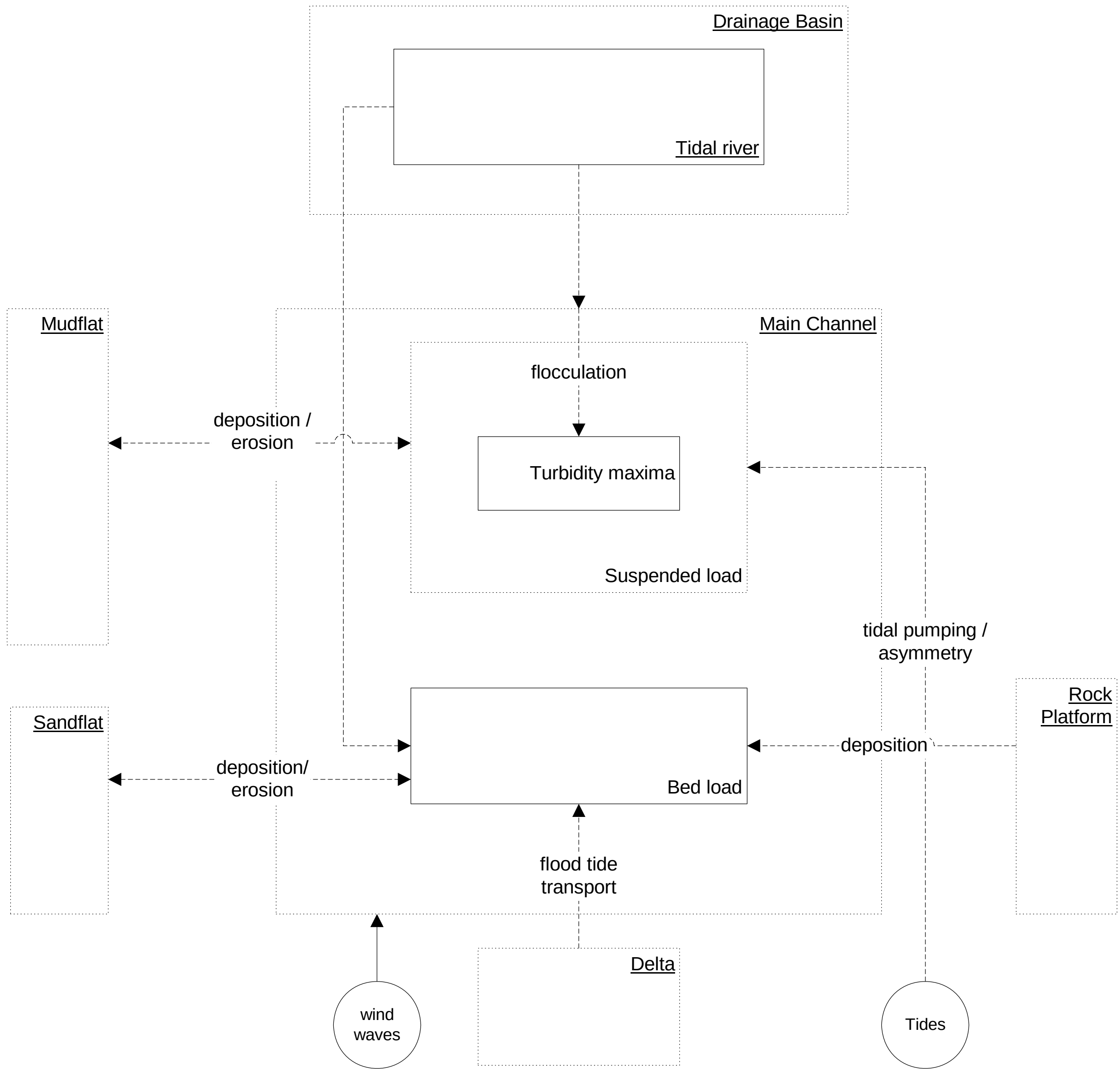
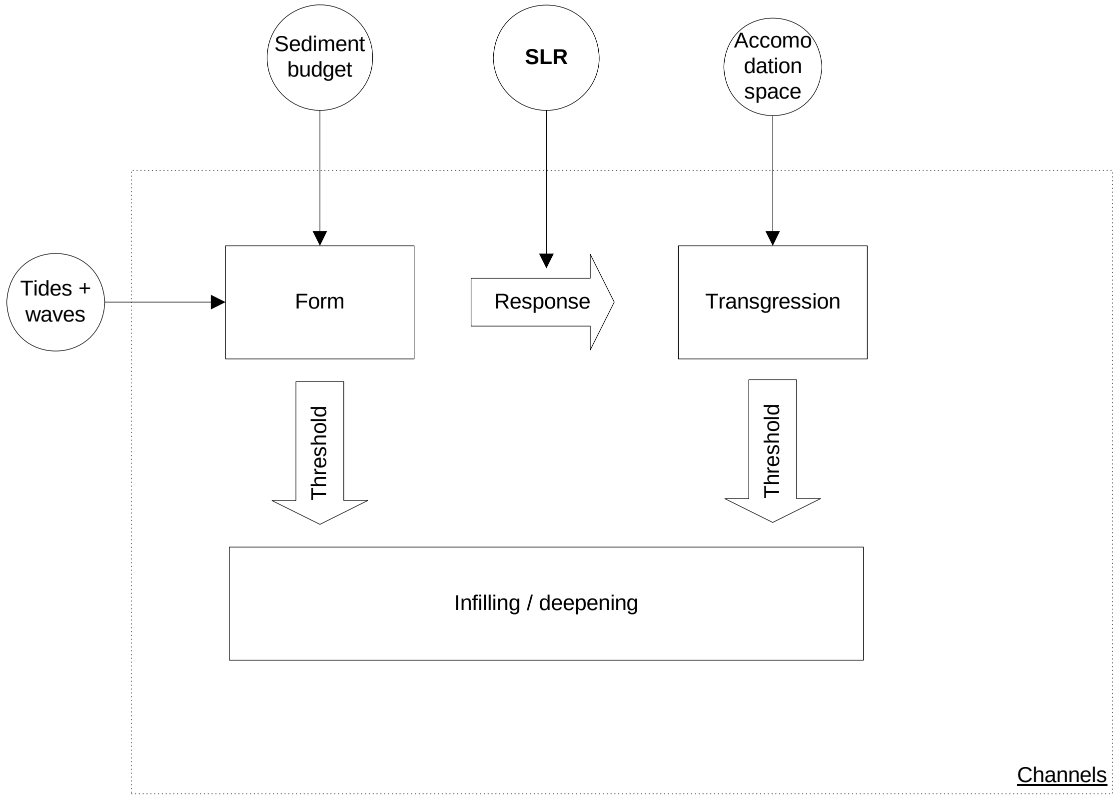
Interaction with other elements - Channels



Short to medium term system diagram - Channels



Medium to long term systems diagrams - Channels



Appendix H: Behavioural Description for Mud Flats

Definition of Geomorphological Element

Intertidal mudflats can be defined as accumulations of cohesive sediments found along the margins of estuaries where there is a sufficient supply of fine grained sediment and prevailing conditions that permit their deposition in intertidal areas. Mudflats occur in estuaries from around the mean low water mark to around the mean high water mark. Therefore mudflats are often bounded to their seaward side by the subtidal channel of an estuary and to the landward side they translate into areas of saltmarsh. In areas where saltmarsh is absent on the landward side of the mudflat the flat may be bounded by some form of sea defence or the rising topography of the hinterland.

Function

Within an overall estuarine system, a mudflat performs a number of functions. In terms of energy, the main function is the dissipation of wave and tidal energy. In terms of sediments, the mudflat can act as a source or a sink for fine grained sediments depending on variations in the factors controlling mudflat development.

Formation and Evolution

It has been suggested that there are two end conditions, or profiles states, in terms of mudflat cross-shore profile shape (Kirby, (1992) (See Figure H1). These two profile states can be related to the general behaviour of the profile and the prevailing forcing processes.

- Convex Profile: This profile shape involves the steepest (i.e. highest gradient) section being located close to the low water mark (i.e. the lower mudflat). The minimum slope will be towards the upper end of the profile (i.e. the upper mudflat). This profile is associated with depositional processes, whereby there is a net increase in sediment on the mudflat over time (Dyer, 1998).

- Concave Profile: This profile involves the maximum slope occurring at the upper mudflat with the minimum slope close to low water. This profile shape is associated with erosion and a net deficit in terms of sediment input. This type of profile is often characterised by a small cliff at the saltmarsh - mudflat boundary. This feature is present due to the fact that a steep slope occurs at the top of the profile concentrating wave attack at high water over a narrow area of mudflat (Dyer, 1998)

Characterising a mudflat according to profile shape provides a good initial basis with which to understand the behavioural trends of this geomorphological element. As profile shape can be related to behavioural trends such as erosion or deposition, these trends can in turn be related to the processes that are dominant in causing, or controlling, the trends. The convex, depositional profile is generally associated with mudflats dominated by tidal flows whereas a concave, erosionary profile is generally associated with mudflats dominated by wave action.

Relating profile shape to behaviour is, however, a general rule and cannot be universally applied. The contradiction of this general rule is likely to reflect the influence of another factor on behaviour or the occurrence of a constraint to morphological development that prevents the natural behavioural tendency. One influence on profile shape that has been suggested is shore plan shape, with lobate shorelines demonstrating slightly more concave profiles and embayed shorelines a less concave profile.

In reality mudflats are likely to be between these two end states of concave and convex and it is possible that elements of both will be present within the same profile. As such, the profile at any point in time will reflect the dominance of the various driving forces and constraints at that time.

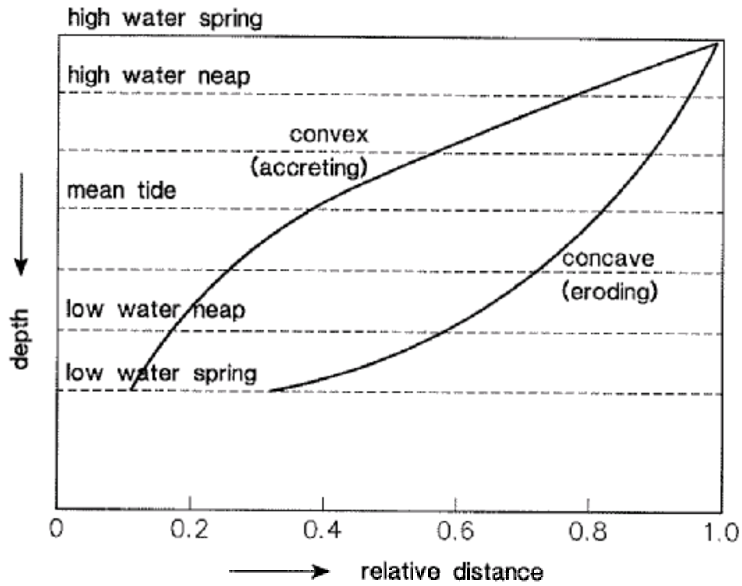


Figure H1. Characteristic Concave and Convex Mudflat Profiles (van Rijn, 1998)

General Form

Mudflats can be subdivided by their cross-sectional profile. This profile can be conveniently divided into three sections, as follows (Dyer, 1998):

- The lower mudflat: from mean low water springs to mean low water neaps;
- The middle mudflat: from mean low water neaps to mean high water neaps; and
- The upper mudflat: from mean high water neaps to lower margins of saltmarsh or mean high water springs.

On this profile a distinctive break in gradient often exists within the middle mudflat, distinguishing the lower from the upper mudflat.

A number of morphological features are often present on the mudflat profile. Channels cutting through the mudflat have a variety of forms and vary in depth and nature according to their location on the mudflat profile and the width of the flat. The occurrence of cliff features within the mudflat are generally an indication of erosional processes (Dyer, 1998), although it should be noted that these features can also be formed in accretional environments. Most commonly these features either occur at the upper limit of the mudflat (i.e. at the boundary with saltmarsh) or around mid-tide level, where the break in slope between the upper and lower mudflat occurs.

General Behaviour

The behaviour of the mudflat will be dictated to a large extent by the balance between erosion and deposition processes.

Deposition
Cohesive sediments are fine grained and as such will be transported as suspended load as opposed to bedload. Deposition of suspended sediments will occur when the settling velocity of the sediments is greater than the shear velocity of the flow. In accordance with this the rate of deposition will therefore, be controlled by the velocity of flows, suspended sediment concentrations and the grain size of material in suspension.

The grain size of a suspended sediment particle will determine its settling velocity. This will, in the case of cohesive sediment, be relatively low and based on this velocity alone a particle would not have sufficient time, even during slack water periods, in which to settle through the water column and deposit on the mudflat. However, the process of flocculation makes the deposition of the fine grained, cohesive sediments on a mudflat possible.

Erosion
Erosion of mudflats mainly consists of the re-suspension of cohesive sediments. The rate of erosion is controlled by the balance between wave and current induced shear stress and mud shear strength and the duration of exposure of sediments to wave attack and flows.

The shear stress imposed, by waves on the mudflat is determined by the wave height and the water depth (as a function of tidal range as discussed above).

The shear strength of the mudflat (i.e. the erodibility) will be determined by a number of factors. The most influential of these is de-watering of the deposited sediments. This occurs during exposure to the atmosphere due to the fall of the tide. The decrease of surface moisture content that occurs during the de-watering process results in cohesion. This cohesion has the effect of raising the threshold for sediment erosion. Biological processes can also impart additional strength on the sediments (e.g. algae acting to bind sediment together).

Wave Current Interactions
The above sections have discussed the relative important of waves in exerting a control on the erosion of mudflat sediment and tidal current in the deposition of sediment on the mudflat. These roles can be explored further to provide an insight into how their interaction exerts a control on mudflat behaviour and hence form. Waves are rapidly attenuated across a mudflat and refracted to be approximately shore normal. Wave action acts to stir up the bed and re-suspend sediments. The subsequent transport of these sediments is however, then controlled by tidal flows.

Biota
It is also important to recognise the role of biota in exerting an influence on the processes of erosion and deposition on an intertidal mudflat. This is the subject of ongoing research attempting to further understanding and quantify the influence of biota. Within the EstProc (EstProc, 2004) project investigations have focused on quantifying the impact of biota on estuary hydrodynamics and sediment dynamics.

In broad terms the influence of biota can be grouped into stabilising processes or destabilising processes. These processes will obviously exert an influence on erodibility, either contributing to accretion or erosion across a mudflat.

Forcing Factors

The processes of transport erosion and deposition of suspended sediments are driven by the forcing from waves and tidal currents.

Wave processes across mudflats will largely dictate erosion, or re-suspension, of sediments across the mudflat profile. Sediment cohesion following deposition and exposure of material will raise the erosion threshold such that re-suspension by tidal currents on following tides is less likely. As a result of this, waves control mudflat erosion and ultimately provide a check on mudflat morphology.

The duration of wave attack is a crucial factor determining the degree of erosion. The period over which any particular location on a mudflat profile is exposed to wave attack is a function of tidal range. Typically, tidal range therefore exerts a fundamental influence, or constraint, on the extent of intertidal mudflat in an estuary. Intuitively, considering this principle, the greater the tidal range, the shorter the duration of wave attack at high water and therefore the greater the extent of fine grained mudflats. Mudflats are likely to be much more extensive in macro- relative to meso- tidal estuaries.

Due to the relatively low settling velocities of cohesive sediment, settling through the water column and deposition on the mudflat surface is unlikely to occur under wave action. Tidal flows across mudflats largely dictate deposition of sediments on the mudflat. As tidal level rises, velocities increase until around the mid-tide level, when half the flats are covered and velocities are at their maximum. As the tide reaches the upper mudflats at high water, velocities fall approaching slack water (Pethick, 1984). Deposition rates would therefore be expected to be greatest on the upper mudflat. This depositional process associated with varying tidal velocities results in a grading of sediment composition, with sediments on a mudflat fining landwards (Pethick, 1984). In general, deposited sediments can vary from sandy silts below mid-tide to silty clays in the high tide zone.

The role of waves and currents in forcing, and hence controlling form, can also be considered with reference to tidal flat hypsometry (i.e. the distribution of surface area with respect to elevation). Hypsometric trends on tidal flats can be related to the relative dominance of waves or tidal currents. Under wave domination, a concave hypsometry results while a higher relative importance of tides leads to convex hypsometry and long term accretion. Plan shape has also been shown to exert a significant influence on tidal flat hypsometry, with this influence of equal importance to the dominance of either waves or tides.

Evolutionary Constraints

A number of constraints to mudflat development can be identified:

- Suspended Sediment Supply: The process of mudflat formation and subsequent evolution is dependant on a supply of cohesive sediment. This supply is required to allow the mudflat to adjust to the applied driving forces. The development of a mudflat under a scenario of adequate suspended sediment supply and a deficit in supply would be significantly different.

- Migration Space: The dynamic nature of mudflats mean they require space in which to migrate in response to changing conditions. A lack of migration space will constrain the position of the mudflat profile and result in different behavioural trends. There are many forms of constraint that fall under the overarching migration space heading. These can be either natural (such as a geological hard point or rapidly rising hinterland topography) or man made (such as sea defences).

- Tidal Range***:*** Tidal range can be considered a constraint to evolution in the sense that it will control the extent, and to some degree the composition, of mudflats that can develop in an estuary.

Behavioural Timescales

Short-term (responses within a year)
Over tidal cycles, a process of sediment re-cycling occurs on mudflats. This process involves the transport of material between the upper and lower mudflat on successive tides. This recycling and movement of sediment within the mudflat profile is the mechanism through which the profile is able to respond the variations in forcing over these short time scales.

Medium-term (responses over decadal to century scale changes)
Mudflat behaviour over this timescale is driven by the occurrence of low frequency, high magnitude wave events and intervening calmer periods. A mudflat may exhibit accretional or erosional behaviour depending on the prevailing forcing. This behaviour will be reflected in the mudflat profile. In addition to these changes in form, changes may also occur in the vertical and horizontal position of mudflats over this timescale.

Additionally, over this timescale, mudflat behaviour may be influenced by migration of any adjacent channels, affecting the degree of mudflat exposure. Biotic factors can also play a role in influencing mudflat behaviour. For example, the presence of eel grass can afford a mudflat surface a degree of protection from prevailing surface. Any change in the presence or extent of eel grass may therefore affect behaviour.

Long-term (responses over century to Holocene timescales)
Mudflat behaviour over this longer timescale is driven by relative sea-level rise. The behavioural response to this forcing is variable and dependant on a number of factors. As a result a number of different scenarios can be considered each with different potential behavioural responses.

Under a scenario of adequate supply of suspended sediment and sufficient migration space for the mudflat to migrate into (i.e. no geological or man made constraints) the response of the mudflat would be to accrete vertically and migrate landward to maintain the same position in the tidal frame.

Under a scenario of restricted suspended sediment supply, the mudflat is unlikely to be able to accrete to keep pace with relative sea-level rise. This accretion is required if the mudflat is to maintain its position within the tidal frame. The lack of sediment to achieve this may result in the eventual drowning of the mudflat profile.

Under a scenario of restricted migration space, e.g. through rising topography or a fixed line of sea defence, the mudflat would attempt to migrate landwards. However, with a static landward margin the mudflat would become progressively squeezed between the migrating mudflat edge and the static landward boundary. This is the process of coastal squeeze.

Interactions with other Geomorphological Elements

Saltmarsh

Mudflats and saltmarsh are interdependent geomorphological elements. Given the dependence of the two units it is vital to consider the two in conjunction with each other and to do this each of the links must be clearly defined, as follows:

Mudflat development essentially creates a low energy environment at an elevation relative to the tidal frame that is conducive to saltmarsh development. As mudflats develop, under adequate sediment supply, their ability to dissipate wave energy will increase and as a result the upper mudflat will progressively become a low energy environment. This environment encourages sediment deposition and as a result elevations increase. Hence the mudflat is progressively able to provide a surface at the correct elevation for saltmarsh colonisation.

Under relatively benign forcing conditions, there is likely to be a transfer of sediment from the mudflat surface to the saltmarsh to be deposited on the saltmarsh surface. Exchanges from saltmarsh to mudflat mainly occur during high magnitude low frequency events. Under these conditions, the saltmarsh acts as a temporary sediment supply to the mudflat. This supply is caused by the increased wave energy eroding the saltmarsh and transporting the material onto the neighbouring mudflat. In geomorphological terms, this supply of material allows the mudflat to adjust its profile to the applied forcing through widening and flattening.

In addition, under these storm conditions the saltmarsh provides migration space into which the mudflat can migrate to allow the morphological response of profile widening.

Channel

The channel is the mechanism through which the main forcing factors (tidal flows and waves) are applied to the mudflat surface. The location and nature of the channel will determine the degree of exposure of the mudflat to these processes.

A channel acts as a conduit for sediment transport to the mudflat. Variations in the supply from this source would significantly affect the behaviour of the mudflat. In addition the deposition of sediments within the subtidal channel may affect the availability of sediment for deposition on the mudflat.

Protective Features

For prevailing conditions to allow the formation and maintenance of mudflats, a degree of protection is required. In the middle and upper sections of an estuary, the form of the estuary itself is likely to provide this. However, in the outer sections of an estuary this protection may be afforded by another geomorphological element, such as a spit, a sandflat or an ebb tidal delta.

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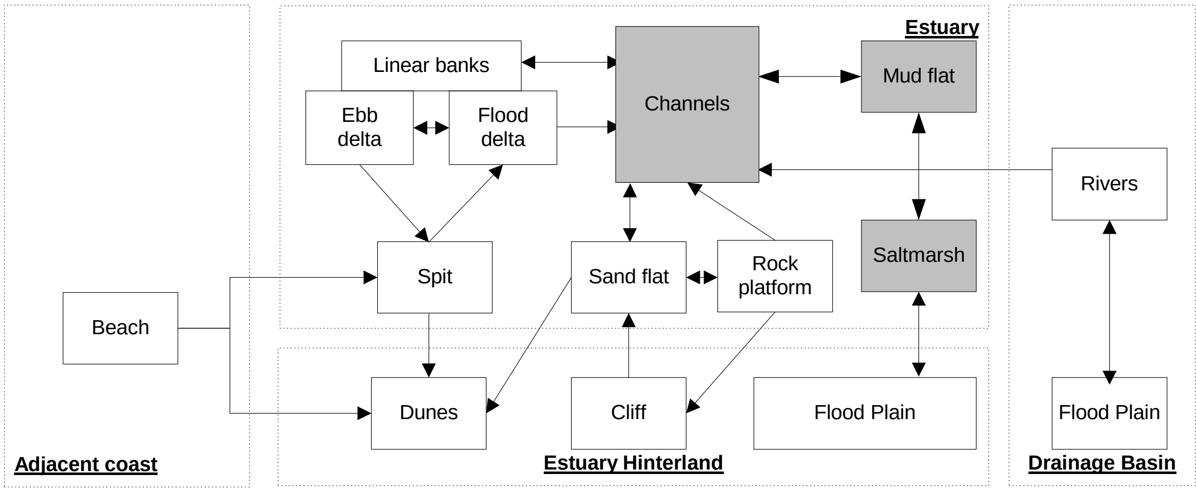
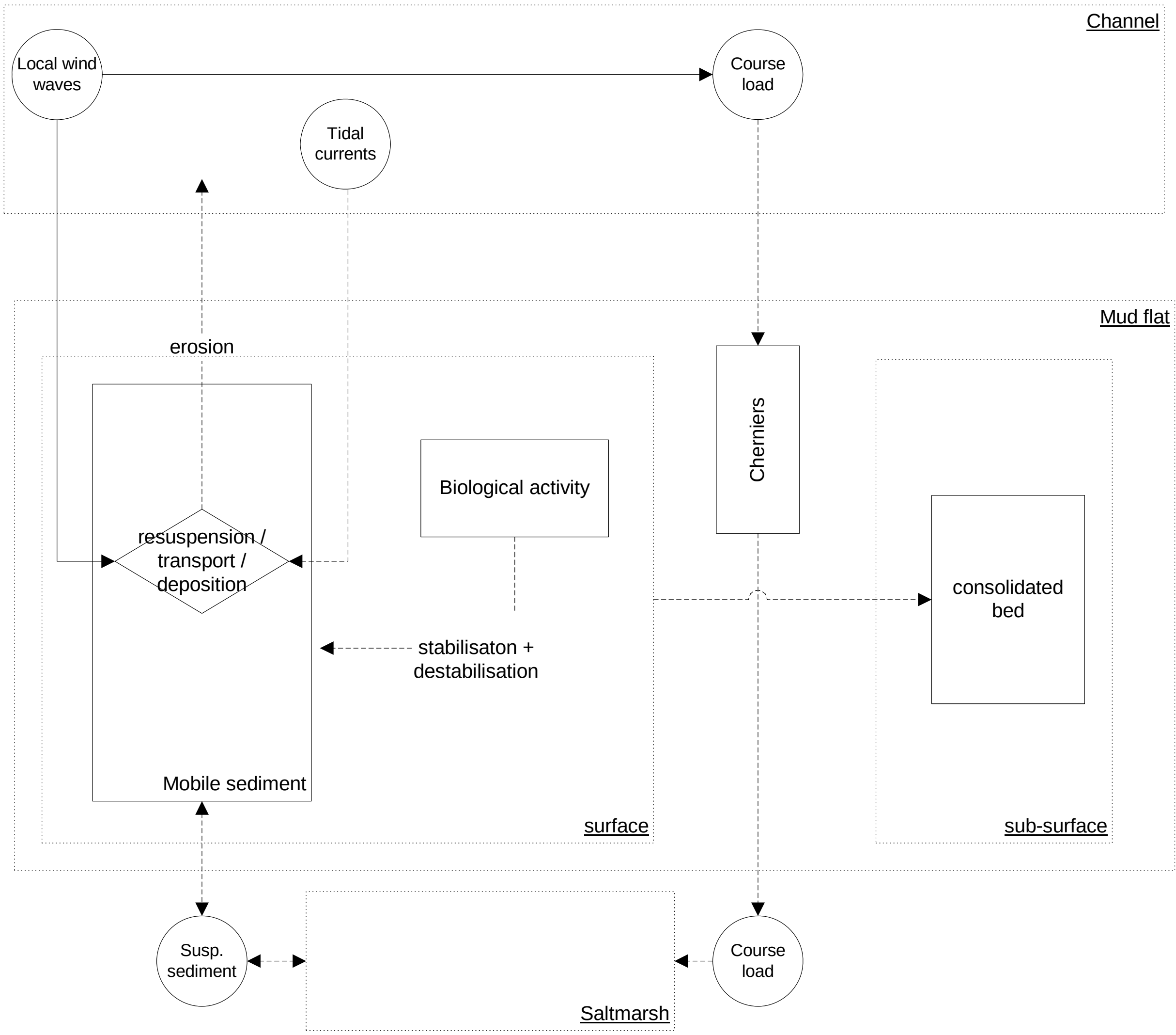
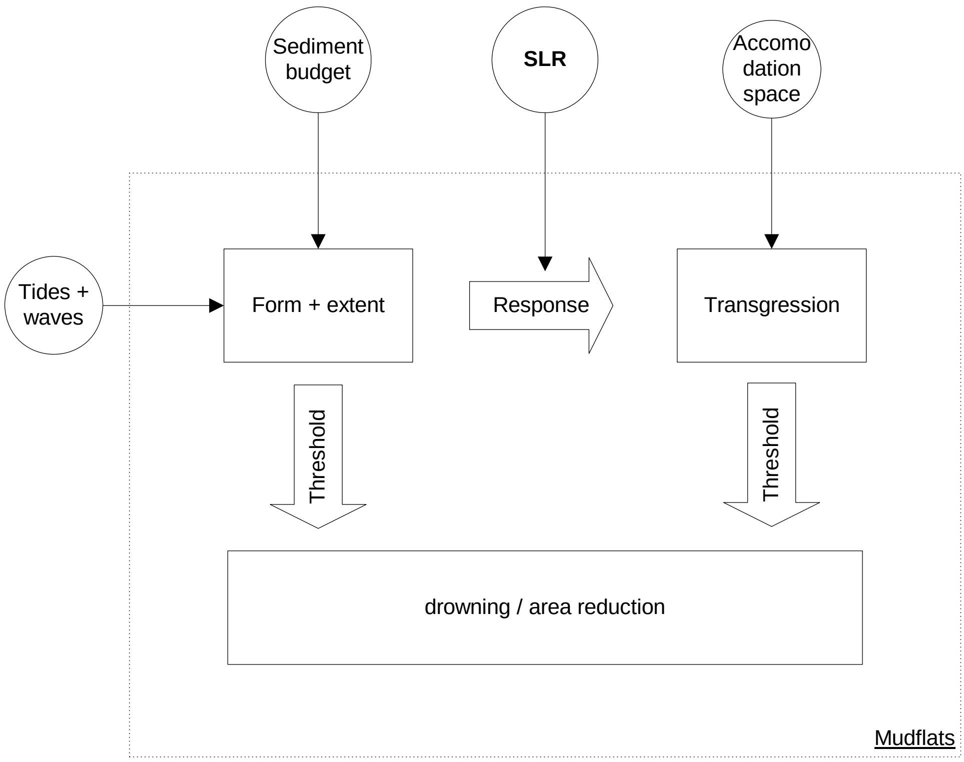
Interaction with other elements - Mudflats



Short to medium term system diagram - Mudflats



Medium to long term system Diagram - Mudflat



Appendix I: Behavioural Description for Sand Flats

Definition of Geomorphological Element

Distinction has been made here, for the purpose of defining morphological behaviour, between mudflats and sandflats. It is recognised that these landforms are part of an intertidal continuum and in many cases will occupy a similar position within an estuary in terms of the tidal frame. However, as noted, the primary concern here is behaviour and the two forms will exhibit subtle behavioural differences. These differences are the product of the differing nature of cohesive and non-cohesive sediments. The resultant changes to behaviour are explored in the following sections. It is recommended that this statement be read in conjunction with the mudflats statement.

Intertidal sandflats are defined here as accumulations of non-cohesive sand sized sediments deposited in the intertidal areas of an estuary.

General Function

The function of a sandflat is the dissipation of wave and tidal energy. This is in common with that of a mudflat. However, differences in the interaction of form and processes, and hence energy dissipation, between the sandflats and mudflats is fundamental to behavioural differences. Sandflats also act as a store of sediment within the estuarine system.

General Behaviour

The behaviour of a sandflat will be linked to the balance between the processes of erosion and deposition. However, the will be a subtle difference in the balance between the two processes on a sandflat relative to a mudflat. This is a critical distinguishing behavioural difference between a cohesive and non-cohesive intertidal area and is dictated by the different responses of the two sediment types to forcing conditions. The key behavioural difference is due to the difference in the critical erosion threshold between the two forms. Mudflat sediments will be more resistant to erosion (Pethick, 1984) with a higher erosion threshold than non-cohesive sandflat sediments. This difference will affect sediment transport on a sandflat and will alter the nature of the behavioural responses of this element over different timescales. Lee & Mehta (1997) note that mud profiles are generally flatter than their sand counterparts.

Forcing Factors

Both tides and waves will play important roles on sandflats. In addition to the direct influence of both these processes, tides will also play a role in behaviour by controlling the location of wave processes across the profile and hence the duration of wave attack. A combination of the tidal range and the sand flat profile will control the width over which wave process will be translated.

Behavioural Timescales

Short-term (responses within a year)

Over the short term, a sandflat is able to alter its profile to adapt to variations in forcing, for example seasonal variations in wave climate.

Medium-term (responses over decadal to century scale changes)

Over this medium timescale, a sandflat is likely to adopt a profile form in response to trends in forcing (for example changes in storminess). In addition to these changes in form, changes may also occur in the position (both vertical and horizontal position) of sandflats within the estuary system over these timescales.

Additionally, over this timescale, sandflat behaviour may be influenced by migration of any adjacent channels, affecting the degree of sandflat exposure.

Long-term (responses over century to Holocene timescales)

Sandflat behaviour over this longer timescale is driven primarily by relative sea-level variations, with the nature of the response controlled by a number of factors. As a result a number of different scenarios can be considered each with different potential behavioural responses. Sandflat behaviour over this timescale is similar to that described for mudflats:

Assuming an adequate supply of sediment and sufficient migration space for the sandflat to migrate into (i.e. no geological or man made constraints), the response of a sandflat under rising relative sea-levels would be to accrete vertically and migrate landward to maintain the same position in the tidal frame.

Under a scenario of restricted sediment supply, the sandflat is unlikely to be able to accrete to keep pace with relative sea-level rise. This may result in the eventual drowning of the profile. Under a scenario of restricted migration space, e.g. through steeply rising topography or a fixed line of sea defence, the sandflat would attempt to migrate landward but would become progressively squeezed between its migrating seaward edge and the static landward boundary. This is the process of coastal squeeze.

Interactions with other behavioural elements

Beach/dune

Sand flats may in certain situation be backed by beach and dune systems to the landward side. Where present, the behaviour of these elements will be closely linked. The formation of a dune system to landward of a beach and sandflat will be controlled by a number of factors. The period of drying will dictate if the required aeolian transport of sands will occur. This will in turn be controlled by the period tidal range and cross-shore profile of sandflat. In addition the sediment composition will exert an influence as will the orientation of the flat with respect to prevailing winds.

Channel

The channel is the mechanism through which the main forcing factors (tidal flows and waves) are applied to the sandflat surface. The location and nature of the channel will determine the degree of exposure of the sandflat to these processes.

The channel will provide the main conduit for sediment transport supplying the sandflat with sediment (sediment may have originally been derived from offshore via longshore drift movement on a spit and through an ebb/flood delta). During erosional events, sediment may also be lost to the channel for redistribution within the system.

Lateral migration of a channel may erode a sand flat, thereby releasing sediments into the estuary system.

Cliff
In a situation where a sandflat is directly backed by a cliff, cliff erosion can provide a direct feed of material during high energy conditions. A sandflat will also provide energy dissipation to a backing cliff feature providing protection.

Rock Platform
In the case where a rock platform is present, overlying sandflat sediment may aid erosion of the rock platform through abrasion but can also provide protection from direct wave attack.

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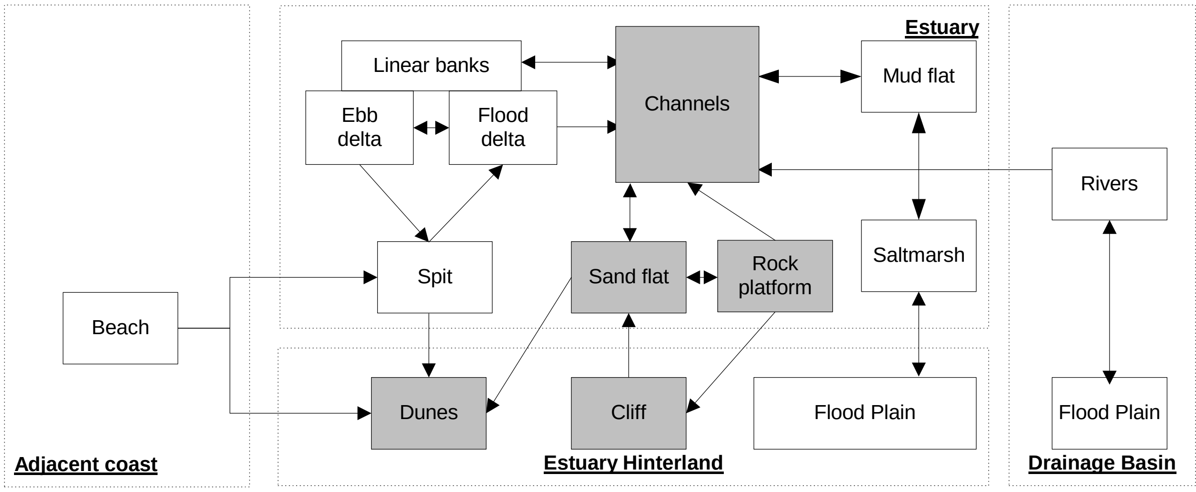
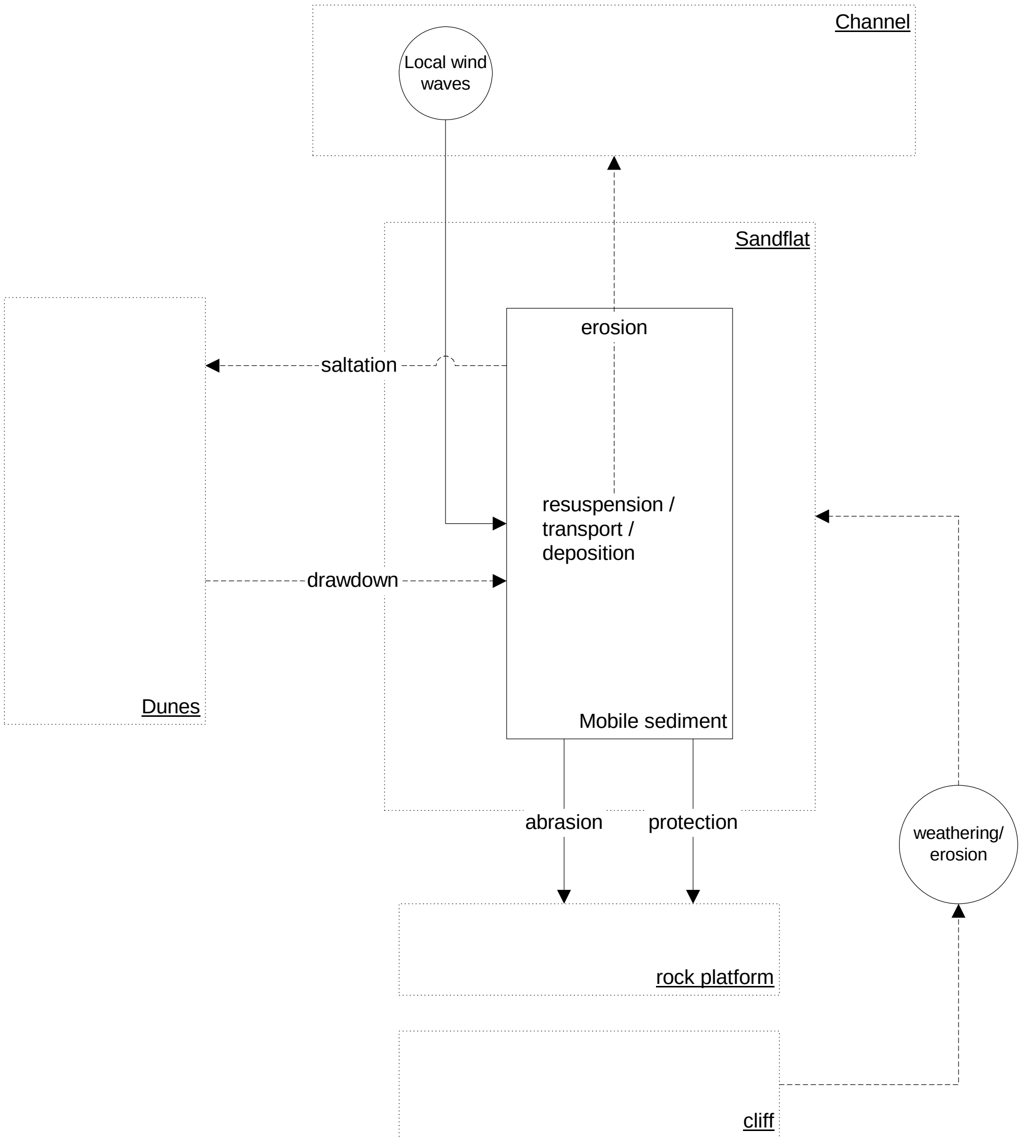
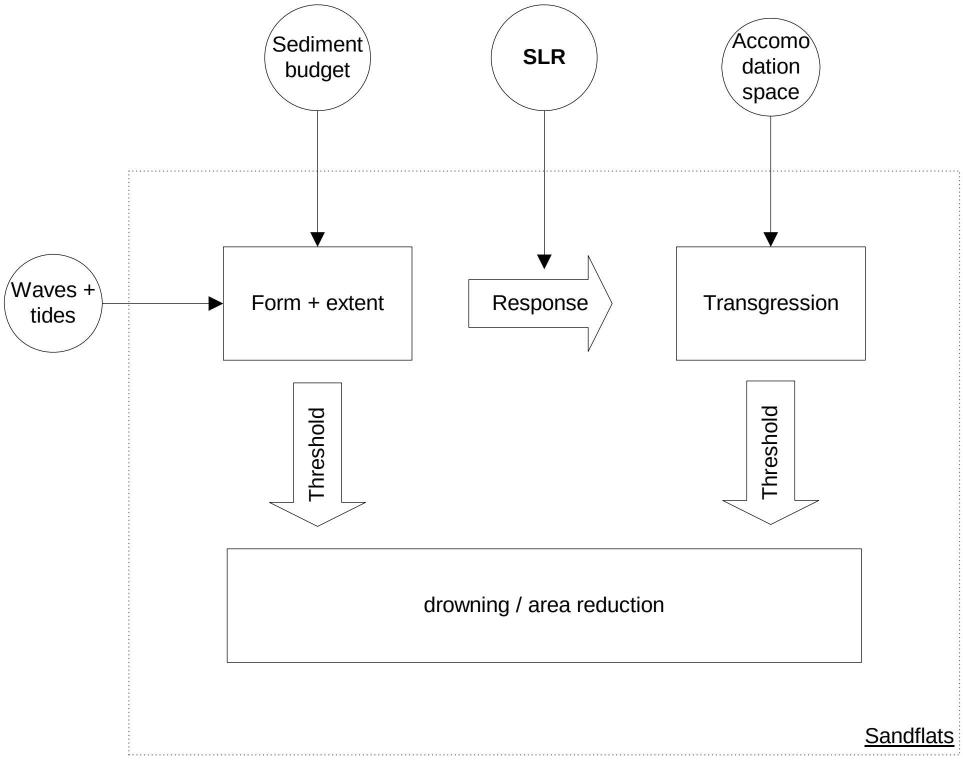
Interaction with other elements - Sandflats



Short to medium term system diagram - Sandflats



Medium to long term system diagram - Sandflats



Appendix J: Behavioural Description for Saltmarsh

Definition of Geomorphological Element

Saltmarshes can be defined as accumulations of cohesive sediments vegetated by salt tolerant plant species found along the intertidal margins of estuaries. Saltmarshes generally occupy the upper inter tidal zone at higher elevations of mudflats, in areas inundated less frequently by the tide in the UK. Typically saltmarshes occur between mean high water neaps to high water spring tides. Above this elevation, the marsh is likely to give way to either terrestrial fresh water plant species or some form of defence or sea wall or the rising topography of the hinterland. At its lower margins saltmarsh is likely to be bounded by mudflat. In areas without mudflat, saltmarsh may adjoin the main sub tidal channel of an estuary or lie in the lee of a feature that acts to dissipate tidal and wave energy. The presence of vegetation on the saltmarsh surface results in significantly different processes, morphology and behaviour relative to neighbouring mudflats.

Function

Within the overall estuary system areas of saltmarsh act to dissipate wave and tidal energy and hence afford protection to the adjacent hinterland, in addition a saltmarsh represents a significant sink for sediments within the estuary.

Formation and Evolution

For saltmarsh to develop there is a requirement first for a sandflat or mudflat to form and evolve. For this to occur the prevailing conditions must be conducive to the transport and deposition of cohesive sediments. This requires a relatively sheltered low wave energy environment with adequate supply of suspended sediments. Eventually, as elevations rise at the upper mudflat, this process will lead to a decrease in the duration of tidal inundation on the upper intertidal (Pethick, 1984). A critical point will be reached where the duration of exposure of the mudflat permits colonisation by halophytic (salt tolerant) vegetation.

The higher the tidal range the larger the vertical range of any saltmarsh habitat. In terms of tidal inundations, sites with elevations that will experience less than about 450 tidal inundations would be expected to develop saltmarsh, whereas mudflat will develop at levels that experience greater that 500 inundations per year (Burd, 1995).

Initial colonisation is likely to occur on mudflat areas of higher elevation than the surrounding intertidal. These higher elevation areas could be the result of a number of factors, such as:

- Organic activity; and
- Relatively higher areas between pre existing mudflat channels.

The establishment of this initial vegetation then encourages further sediment deposition and further colonisation, forming patches of vegetation (Pethick, 1984). In addition, marshes may grow up around existing creeks within intertidal flats. Patches of developing vegetation will, over time, become joined to form a continuous area of vegetation. As this development takes place, important changes also occur to the flow regime across the newly formed marsh.

Flow becomes more confined to channels or creeks. As accretion of the marsh surface occurs the number and duration of tidal inundations is further reduced. This allows different plant species to colonise these higher levels of the marsh.

Over the long term the rate of deposition decreases as the reduced tidal inundations limit the sediment supply. A marsh matures asymptotically, towards an elevation at which further deposition is sufficient to offset the effects of relative sea-level rise and compaction.

General form

When considering the form and behaviour of areas of saltmarsh it is convenient to consider the different geomorphological features that are present within this element. Four principal component features occur on areas of saltmarsh. These are:

- Saltmarsh surface;
- Creeks;
- Salt pans; and
- Cliffs.

Each of these features will be controlled by different processes and hence will perform a different function or role within an overall area of saltmarsh. However, it is the combination and interaction of each of these features that will determine the behaviour of the saltmarsh system as a whole. The processes associated with each of these features are discussed below.

Saltmarsh Surface

A large proportion of saltmarsh area is marsh surface. The saltmarsh surface plays a role in the dissipation of wave and tidal energy. Studies regarding the role of the marsh surface in wave attenuation have shown that wave height reduction over saltmarsh is approximately four times higher that over sand flats. In addition, the marsh surface acts as a significant sink for sediments.

Marsh surface behaviour will vary both vertically and horizontally in the long term. Vertical variations will occur as the marsh matures in a feedback relationship between elevation, tidal inundation and sedimentation. Short term vertical variations may also occur, driven by variations in, for example, suspended sediment concentration and biological activity.

The cross-sectional shape of a saltmarsh is likely to vary over time. The variations are a reflection of spatial variations in sediment deposition across the marsh surface. A convex profile will be produced when sedimentation rates are greatest towards the centre of the marsh, falling off to landward and seaward, whereas a concave profile will be the result of deposition towards the upper or lower sections of the marsh. A number of factors will control the shape of the saltmarsh profile, not least the maturity of the marsh, i.e. the stage of development of the marsh will dictate where on the marsh surface the zone of maximum accretion occurs.

The typical mature cross sectional profile of a saltmarsh can be characterised as convex - concave (See Figure J1) (Pethick, 1984). At the seaward margin the saltmarsh exhibits a convex profile, with a flat main central section and a concave landward slope. This profile is a reflection of the number of tidal inundations and therefore the likely deposition rates i.e. a convex lower slope indicative of deposition processes at the lower marsh where inundation numbers and durations will be highest and the concave upper marsh landward slope located in an area of limited inundation and hence limited deposition (Pethick, 1984).

In horizontal terms, the marsh surface may extend or migrate landward or seaward. The seaward limit of the saltmarsh surface can be marked by the presence of a cliff feature up to 1m in height. These cliffs can be formed and develop in both an erosional and accretional environments.

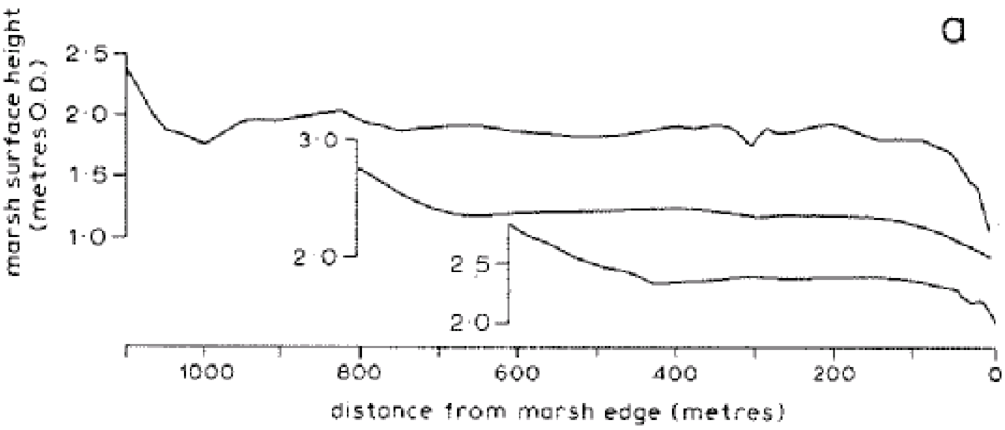


Figure J1. Profile Across Saltmarshes in the Tamar Estuary (Pethick, 1984)

Marsh Creeks

The creek systems found within saltmarshes are a vital component of the overall system. In plan view, creek systems appear similar to fluvial drainage systems. However more detailed consideration shows distinct differences between the two. Flows within saltmarsh creeks are two way and in addition saltmarsh creeks experience bank full conditions on a regular (tidal) basis. Investigation of the surface area of marshes and the relation to creek density suggests that the main function of the creeks is not drainage of the ebb tide from the marsh. Rather the details of the creek systems appear to be dependent on the tidal prism entering the marsh on the flood tide. This suggests, therefore, that the function of saltmarsh creeks is to dissipate tidal and wave energy in a similar way to a main estuary channel. In addition, marsh creeks can also act to drain freshwater flows.

Creeks act to funnel the oncoming flood tide and distribute the tidal water into the marsh (Carter, 1988). The creeks transfer water through progressively smaller channels thereby dissipating the tidal energy through increased friction. As water levels in the creeks rise and the banks are overtopped water is allowed to spill onto the marsh surface (Carter, 1988). The increased frictional resistance on the surface then causes deposition of sediments in suspension. From this perspective the creeks perform an irrigation function transporting water and, hence suspended sediments, to the marsh surface.

In addition to transporting suspended sediments associated with tidal flux, flow in the creeks also acts to recycle sediments within the marsh system (Carter, 1988). This occurs as creek banks are undercut causing bank slumping. The sediment produced by this process may be transported seaward or alternatively (i) re-deposited in creeks or (ii) deposited on the saltmarsh surface. Within the creeks, deposition is most likely to occur in the vicinity of creek meanders. On the saltmarsh surface, areas of greatest deposition occur adjacent to the creeks as material is deposited immediately after spilling onto the marsh during bank full stages of the tide. This results in the formation of levees (Carter, 1988). Levee deposition of this sort will in term effect the nature of the local colonising species.

Salt Pans
A further common saltmarsh feature is saltpans. These consist of shallow pools filled with water on the marsh surface. Although these features are an element of the overall saltmarsh form they are essentially relict features, as defined above, and are therefore not included as a component within the systems diagram.

Cliffs
A cliff feature regularly occupies the transition zone between mudflat and saltmarsh zones and indicates the boundary between mobile mudflat sediments and the more stable saltmarsh sub-surface, which is influenced by the vegetation root structure. It is believed that these features can occur in both erosional and accretional environments (Gao & Collins, 1997) and under wave action (local wind waves or ship wash) these zones can be come highly dynamic.

General Behaviour

Much of the behaviour of a saltmarsh is dependant on the balance between the processes controlling erosion and deposition.

Deposition
As an area of mudflat becomes colonised by saltmarsh species, the nature of the deposition processes are dramatically altered. Saltmarsh vegetation presents an increased frictional roughness to the intertidal surface. This results in two specific impacts on the flow regime above the saltmarsh surface. Firstly, a zone of zero velocity occurs close to the bed. Secondly to compensate for this dramatic decrease in the lower layers of flow, the upper layers of the flow increase in velocity. The net result of this is actually a lower sedimentation rate on a saltmarsh relative to a mudflat. However, reduced near bed velocities protect the recently deposited sediment from re-suspension and as a result saltmarsh tends to accrete far more rapidly than mudflat.

In addition to this basic process, the presence of vegetation on the saltmarsh surface exerts several other important influences on deposition, for example:

- Plant stems set up flow eddies trapping sediments and resulting in areas of high deposition;
- Increases in flocculation locally can be caused by plant species that provide salt from their stems increase salinity levels. This increased flocculation could, in theory, lead to increased deposition; and
- Saltmarsh plants may be underlain by algal mats producing a sticky surface which traps sediments more effectively.

Deposition of sediments on a saltmarsh can occur on differing parts of the marsh, including:

- Saltmarsh Surface Accretion: The main mechanism of marsh growth and expansion is deposition on the marsh surface. This can cause the vertical and/or horizontal development of the marsh; and

- Creek Deposition: Sediment may also be deposited within tidal creeks either from the re-working of pre-existing saltmarsh sediment or the introduction of new sediments.

Erosion

Due to the frictional influence of saltmarsh vegetation on flows, erosion of a saltmarsh through the re-suspension of fine grained sediments is less frequent than erosion on neighbouring areas of mudflat. Erosion of saltmarsh sediments will occur when the shear stress imposed by physical processes exceeds the shear strength of the saltmarsh surface.

As with deposition, saltmarsh erosion can occur in relation to any of the geomorphological features identified, as follows:

- Erosion of the marsh edge (cliff);
- Enlargement of the pans or creeks. This process can occur via either bank collapse or headward erosion/retreat and may result in the occurrence of areas of bare un-vegetated mudflat within the marsh; and
- Marsh surface erosion. The deterioration of marsh vegetation can lead to generalised scour and surface lowering.

The process of erosion and deposition and hence the behaviour of a saltmarsh should also be viewed in the context of biological interactions.

Biota

It is also important to recognise the role of biota in exerting an influence on the processes of erosion and deposition on an intertidal mudflat. This is the subject of ongoing research attempting to further our understanding and quantify the influence of biota (EstProc, 2004). In broad terms the influence of biota is exerted through a number of processes that can be grouped into stabilising processes or destabilising processes. These processes will obviously exert an influence on erodibility, either contributing to accretion or erosion across a mudflat.

Forcing Factors

The processes of erosion and deposition discussed above are driven, in the case of saltmarsh, by the two principal driving forces of waves and tidal currents.

Wave processes in marsh areas will dictate the erosion or re-suspension of sediments. However, due to the high position of areas of saltmarsh within the tidal frame, both the frequency and the duration over which the saltmarsh surface will be exposed to wave attack is limited relative to seaward areas of mudflat and can lead to changes in saltmarsh area.

Tidal processes across saltmarshes largely dictate deposition processes. Tidal processes transport suspended sediment onto the saltmarsh. Tidal flows are distributed through the marsh area via the marsh creeks and, at higher stages of the tide, over the marsh surface itself.

As noted, the tidal stage will also regulate wave attack and in this sense exerts an indirect influence on marsh erosion.

Evolutionary Constraints

A number of constraints to saltmarsh development can be identified:

Suspended Sediment Supply
Sediment supply to the saltmarsh surface is critical to the depositional processes that are central to the formation, evolution and maintenance of saltmarshes. The rate of deposition is dictated by suspended sediment concentrations in the tidal water over the marsh surface. Variations in sediment supply will significantly affect the way in which the saltmarsh behaves in response to the applied driving forces.

Migration space
A saltmarsh is a dynamic landform. In order for this landform to respond to changing forcing, there is often a requirement for migration space. This is essentially space into which the saltmarsh is able to migrate. The behaviour of the saltmarsh may be significantly different if there is a constraint imposed on the migration space. This constraint could be in the form of a natural factor (such as a geological hard point or rapidly rising hinterland topography) or man made (such as sea defences).

Behavioural Timescales

Short-term (responses within a year)
Over the tidal durations, water and sediment exchanges occur that are critical to sustain the vegetation on the saltmarsh surface. The saltmarsh surface is subject to periodic tidal inundation, the frequency and duration of which is dictated by the elevation relative to tidal levels, supplying suspended sediment. Flows and suspended sediments are affected by the frictional influence of the vegetated surface providing the potential for sediment deposition. This periodic cycling of sediment onto the saltmarsh surface over a tidal frequency provides the means for saltmarsh morphological response.

Medium-term (responses over decadal to century scale changes)
Over this medium timescale, the behaviour of a saltmarsh will be dictated by the saltmarsh response to low frequency high magnitude wave events and intervening tidally dominated calmer periods. During storm events, erosion of the saltmarsh is likely to occur and marsh edge erosion will act as a sediment supply to the adjacent mudflat, thus allowing the two elements to respond to the applied forces. During these periods it is also possible that the boundary between the saltmarsh and mudflat (potentially marked by a cliff feature) will migrate landward. These erosional processes are replaced with depositional processes during the tidally dominated intervening periods. In these calmer periods sediment is transported onto the marsh area via the fronting mudflat and deposited. This allows marsh recovery to occur (both vertically through deposition on the marsh surface and horizontally through recovery seaward of the marsh edge).

It is also possible for biotic factors to influence saltmarsh behaviour over these timescales. The influence of Spartina *(Spartina anglica*) in UK estuaries is an example of this. The grass spread, partially naturally and partially due to deliberate introduction, in the late 1800s and early 1900s and resulted in initially rapid sediment accretion (Toft *et al*, 1995). The subsequent regression of Spartina then led to saltmarsh erosion.

Long-term (responses over century to Holocene timescales)
Saltmarsh behaviour over this longer timescale is driven by primarily by relative sea-level change. Relative sea-level rise will mean an increase in water depth and hence a change to the frequency and duration of tidal inundation on a particular area of marsh surface. This change will affect marsh accretion rates and marsh development. The actual behavioural response to this change in forcing is highly dependant on the nature of a number of factors, leading to a number of different scenarios:

A scenario can be considered whereby there is an adequate supply of suspended sediment and sufficient landward migration space for the saltmarsh to migrate into (i.e. no geological or man made constraints). Under rising relative sea-levels the marsh surface will rise vertically and translate landward (or potentially advance). Under this response the marsh accretes to keep pace with relative sea-level rise and maintain its relative position within the tidal frame.

Under a restricted sediment supply scenario, the marsh surface is unlikely to be able to accrete vertically to maintain its position in the tidal frame to compensate for the rise in water level. As a result water depths over the marsh will progressively increase and the marsh may eventually drown.

Under a restricted migration space scenario, an area of saltmarsh would attempt to migrate landwards. However, with a static landward margin, e.g. through rising topography or a fixed line of sea defence, the marsh would become progressively squeezed between the migrating saltmarsh edge and the static landward boundary. This is the process of coastal squeeze.

These idealised behavioural responses over the long term assume a monotonic increase in relative sea-level that would lead to a progressive change in forcing with a corresponding response. However, in reality, fluctuations in the rate of change of relative sea-level and the direction of change will occur with corresponding potential for recession as well as progradation.

Interactions with other Geomorphological Elements

General Interactions (Elements within the estuary system)
The exchanges between saltmarsh and mudflats are explored in Appendix H. In addition, the saltmarsh interacts with an estuarine floodplain through the action of flooding and drainage during extreme water levels and rainfall events respectively.

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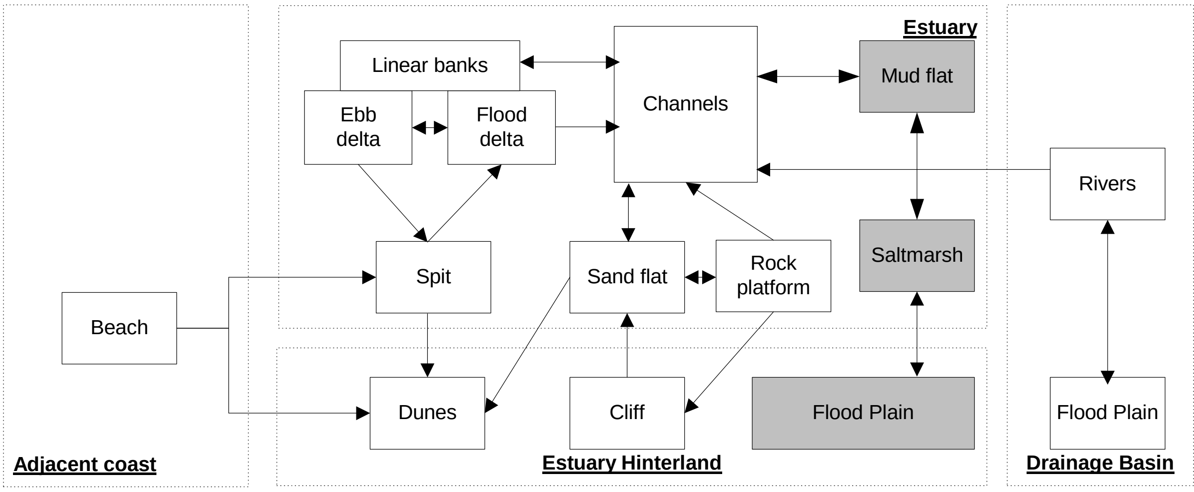
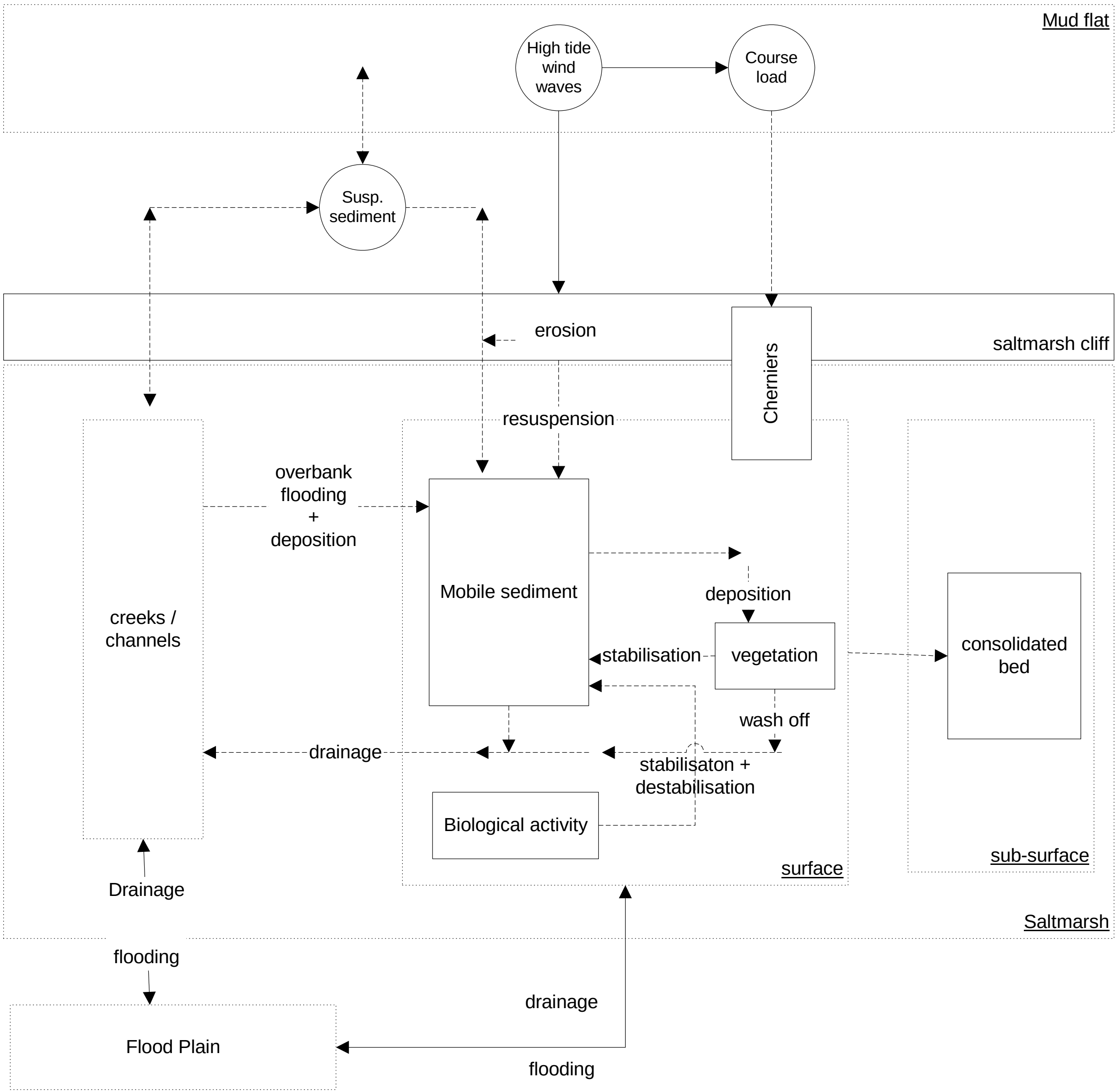
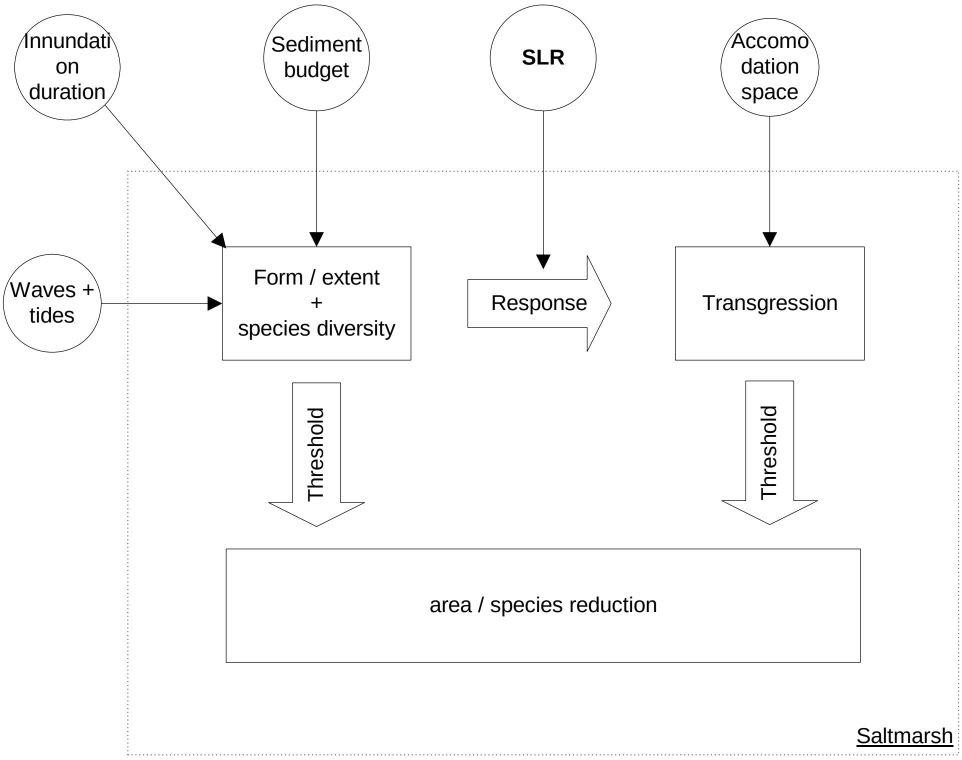
System Diagram (Saltmarsh) - Interactions with other elements



System Diagram (Saltmarsh) - Short to medium term



System Diagram (Saltmarsh) - Long-term



Appendix K: Behavioural Description for Drainage Basin

Definition of Geomorphological Element

A drainage basin is the topographic region from which a river receives its water due to drainage. It can be considered as the area covered by a single fluvial (non-tidal) system with division between other drainage basins defined by watersheds that act as topographical barriers.

Function

The primary role of a drainage basin is to enable the storage and subsequent transportation of water and sediment derived from the local climate and the basin watershed via the river network, to the estuary and sea.

In the context of the estuarine system, the drainage basin therefore regulates the inputs of water and sediment to the system and interacts with the estuarine form and processes. In general terms, UK estuaries are less influenced by fluvial activities than their counterparts in more mountainous regions of the world.

Formation and Evolution

The formation of a river basin is a function of its inherited topographic location. Evolution of its form and characteristics will then result from modification to the key forcing factors that input energy to the system. The climatic conditions have the most important direct influence on the drainage basin characteristics with changes to precipitation regimes and vegetation cover altering other system elements and drainage characteristics. This is discussed in more detail below.

General Form

The inherited relief and geological composition dictates the initial form with ongoing physical processes altering this form through erosion and accretion.

The drainage basin is a morphological feature that is composed of a range of connecting and overlapping elements:

- Topographic surface/catchment;
- River network (rivers, streams and channels);
- Tidal river; and
- Flood Plain;

Topographic surface/catchment
The characteristics of the topographic surface influences many of the internal attributes. Important characteristics and their role include:

- Size of the catchment (volume of water transported);
- Length, shape and relief (rate of water transport - discharge);

- Underlying lithology and soils composition (structure of channel network, channel density and form, groundwater storage and sediment availability); and
- Vegetation (slope stability).

The topographic surface is the route for energy input to the system in the form of precipitation (rainfall and snow) and also losses from the system in the form of evaporation.

Important processes on the topography include, weathering of solid bedrock to supply sediments downslope, rain-splash, sheet, rill and gully erosion, infiltration to provide groundwater flow and surface run-off, which can erode and transport unconsolidated soils and sediments.

River Network
The network of rivers, streams and channels is the primary route for the transport of water and sediment downstream out of the river basin and into the estuary.

The form of the river network can be varied in terms of their length, density, shape (straight, meander or braided), slope, composition and cross-section. The network density is regarded as a fundamental characteristic of a drainage basin since it provides a measure of availability of channel flow (and hence total discharge) which is more efficient than surface or groundwater flow. The form of a river network can therefore be considered as one, which maximises discharge within the context of the topographic and geological constraints and under equilibrium conditions channel form tends to be morphologically stable (in regime).

The form of individual channels is a direct response to the flow received from upstream. This differs from the estuarine morphology where discharge through any one section is coupled to the form of the channel.

An important property of the water transported within the drainage basin is the low concentration of solutes. This property of freshwater prevents flocculation of fine sediments until exchange with saline water (in order of 2ppt) within the estuarine environment.

Key processes within the channel network primarily include those of sediment transport (erosion and deposition).

Tidal River
The lower reach of a river network that accepts tidal and fluvial flow is an important feature as it represents the transition between fluvial and estuarine processes. Its form will reflect the gradual transition between the fluvial environment where form is dependant on discharge and the estuary where form and discharge mutually co-adjust.

Flood Plain
The flood plain is the area of relatively flat land adjacent to the river network. It functions as a temporary sediment store as sediment moves downstream and can also accommodate flood water storage during periods of extreme discharge.

Two processes are responsible for the formation of flood plains:

- Lateral accretion; and
- Overbank deposition.

Within a meander channel, deposition naturally occurs on the convex bend to create point bars during periods of low flow. During high flow erosion occurs on the concave side of the bend. This deposition and erosion cycle accommodates the lateral movement of a channel through the floodplain primarily during below bank flow conditions.

During overbank conditions, where water volume exceeds channel capacity the flood plain is inundated and deposition of suspended sediment occurs across the flood plain or locally to form levees.

It has been noted that the frequency of overbank stage is relatively uniform (typically 1:1-1:2 year event) for a range of rivers in differing regions (Leopold *et al.*, 1964). Coupled with the knowledge that channels do not become progressively deeper as floodplain deposition occurs, implies that under equilibrium conditions the channel form adjusts to accommodate the typical basin discharge and that the floodplain can adjust to accommodate more extreme discharges.

Definition of an estuarine floodplain as a separate morphological form is perhaps unwarranted since as a river channel merges into the coastal setting it can be regarded as part of a continuum. However, there is a transition between dominance of tidal over fluvial processes in a downstream direction and the scale of the river channel increases, as does its stability, and these factors will alter the relationship between the channel and the floodplain.

Where the watershed input to the fluvial system is responsible for overbank conditions in the drainage basin, it is tidal waters that are responsible for flooding of the estuarine floodplain (although this can be in-combination with high river discharges).

Vegetation
Vegetation plays an important role in the drainage basin. Vegetation cover determines the exposure of soil cover, the stability of sub-surface soils (through root structure) and the magnitude of modification of precipitation processes at surface. It therefore can modify the net input to the system (interception and transpiration), affect storage and influence rate at which water and sediments are transmitted through the system.

General Behaviour

The importance of the behaviour of a drainage basin and its component systems lies in its function of transporting water and sediment into the estuary.

An understanding of the lithology of the basin, soil composition and land use informs on the type and quantity of sediment load input to the estuary. Knowledge of the discharge characteristics tells us something about the total volume discharged into the estuary and its distribution through time.

Both sediment and water volume can have an important influence on estuarine dynamics where such inputs are in sufficient proportion to estuarine flows or occur at sensitive periods in time. For instance, fluvial sediment can be an important component of the estuarine sediment budget and extreme water discharges can influence upstream estuary morphology.

The likely influence of the drainage basin on estuarine processes and morphology can be inferred from the ratio between river discharge and tidal prism, although the same analysis for extreme events can indicate the potential for influence on estuary morphology.

Forcing factors

The major forcing factor on the system is the climate that controls precipitation and temperature regimes, and together with the inherited geology, these determine the sediment yield, river network structure and vegetation cover.

Behavioural Timescales

Shor-term (responses within a year)
The nature of river discharge for one gauging station, for instance at the tidal limit is expressed by a flood/storm hydrograph. This shows several important characteristics, including, peak flow, peak flow, total run-off and the rate of discharge rise and fall. When the rainfall is plotted on the same graph, the lag time to peak flow can be determined.

Flood hydrographs will clearly vary according to season for any particular drainage basin as a function of precipitation, temperature, lithology, soil composition and vegetation cover. Over the short-term variations in precipitation will be the dominant process that determines channel discharge and inputs to the estuary.

Medium-term (responses over decadal to century scale changes)
Much of the work within a drainage basin is accomplished by intermediate frequency, moderate magnitude events (extremes) of perhaps only a few times per year. With a long enough time series of discharge measurements annual extreme events can be identified and their relationship to estuary tidal prism understood.

Annual extremes or those over a longer period (shown by a flood frequency curve) may be particularly influential for estuary morphology under equilibrium drainage basin characteristics. Inputs of sediment may have functional importance for the estuarine sediment budget and discharges may alter inner estuary morphology.

Over the decadal period anthropogenic changes in the drainage basin may be important in influencing the interaction with the estuary. Changes to land use such as through agriculture may alter the availability of sediments. Whilst urbanisation and other associated interventions including, bank stabilisation and protection and canalisation is likely to significantly alter the drainage characteristics. Urbanisation reduces surface permeability thereby reducing the lag time of the flood hydrograph and increasing the flood peak and frequency of overbank discharge.

Long-term (responses over century to Holocene timescales)
Over longer timescales, erosion of the drainage basin surface will act to lower its relief and climatic factors will be important for evolving the drainage basin characteristics. Changes in precipitation and temperature regimes coupled with subsequent changes to vegetation cover may evolve the channel network to a new quasi-equilibrium state and result in altered discharge and sediment volume input.

Over this time frame the influence of sea-level rise will become important. Changes to relative sea-level will influence the tidal regime and hence will play an important role in modifying estuary morphology. Where an estuary has sufficient (unprotected) flood plain then sea-level rise can be accommodated by migration of the estuary form both laterally and towards the rive basin at the head of the estuary.

Interactions with other Geomorphological Elements

Estuary Floodplain
In the context of a rising and falling tide it is the intertidal surface that can be considered as the estuary floodplain with flooding on a twice daily frequency (for semi-diurnal tides). In the estuary, overbank condition can be considered as occurring when the tidal elevation exceeds the subtidal channel and water movement occurs laterally across the intertidal.

In an estuary where there is sufficient unconfined accommodation space, then more extreme tidal ranges will overbank the typical high water boundary and flood adjacent land in a manner more analogous to fluvial flooding. However, whilst the fluvial floodplain behaves more as a temporary sediment store for downstream transport, the estuarine floodplain does not over the short timescale appear to have this role, although can accommodate lateral channel movement.

Over long timescales the estuary floodplain can accommodate sea-level rise by allowing space on the hinterland for the estuary form to migrate laterally.

Estuary Channel
The focus of the earlier discussion has been on the interaction between the drainage basin and the estuary. This interaction by way of the tidal river element provides a source of fluvial discharge and sediment (bedload and suspended) into the estuarine setting.

The importance of the suspended load imported into the estuary for other geomorphic elements (mudflats, saltmarsh and estuary channels) will be dependant on the scale of the drainage basin. The scale of the contribution to the estuarine sediment budget from sediment load derived from the drainage basin, will be determined by, amongst other factors, the geology of the basin.

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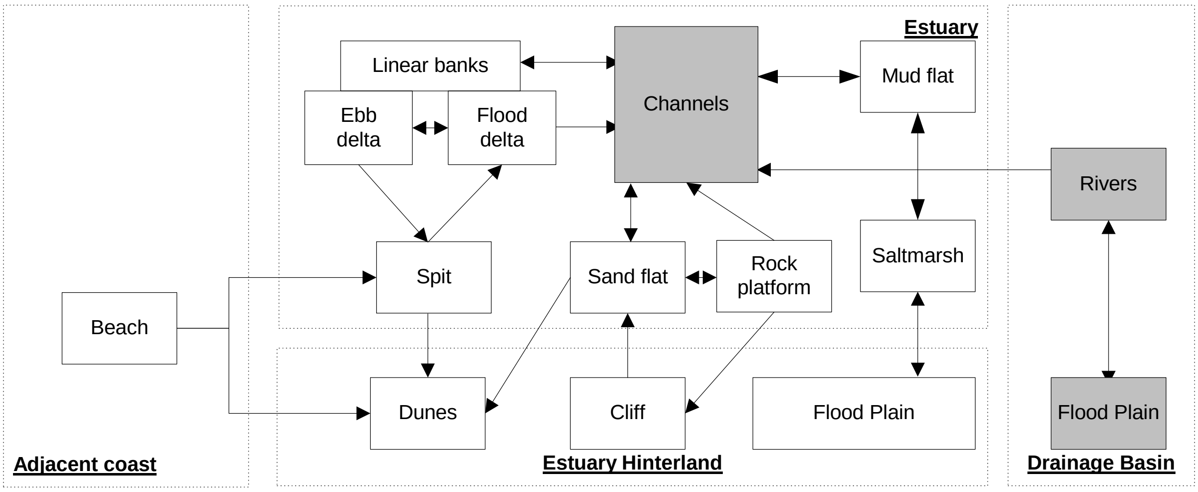
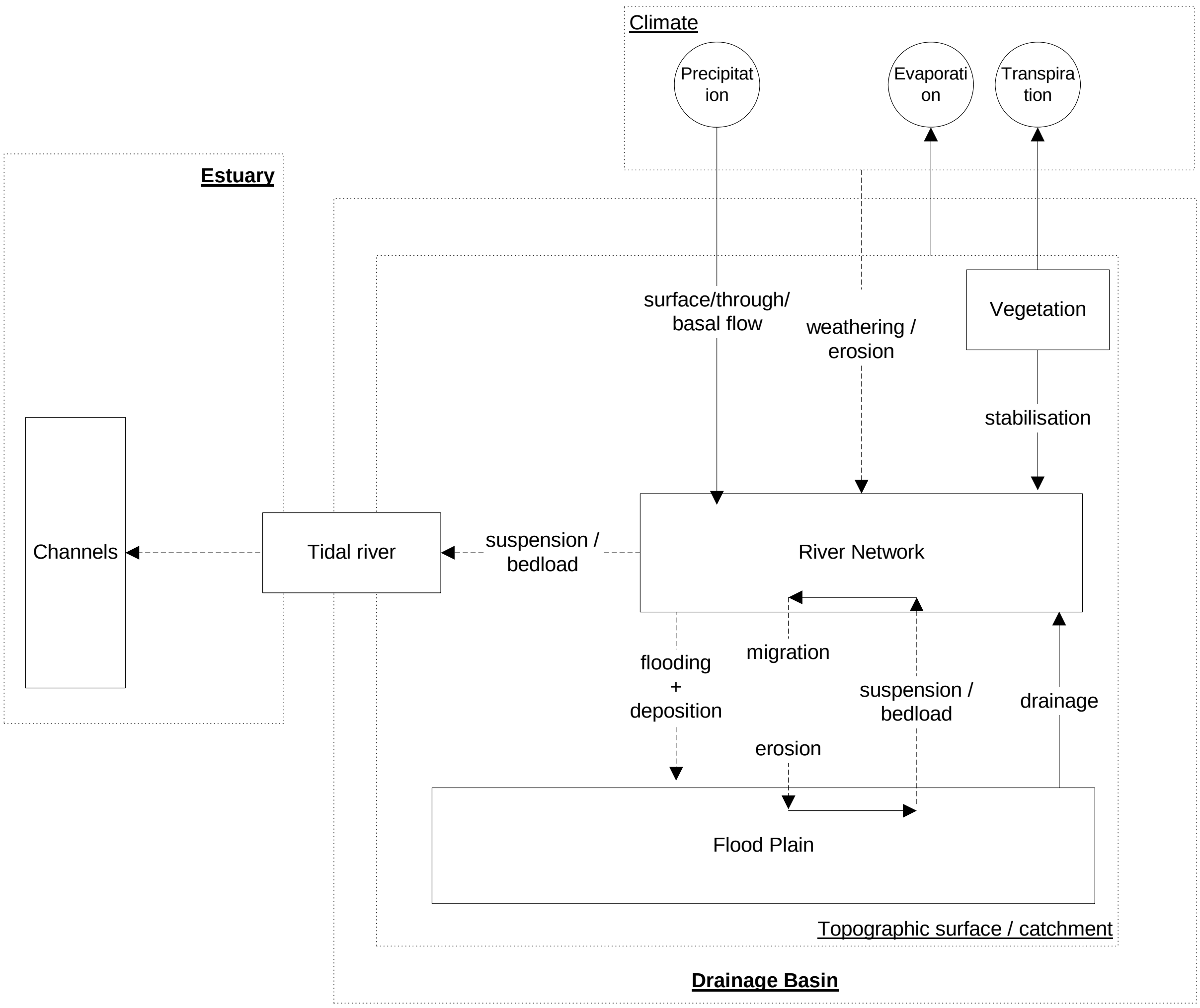
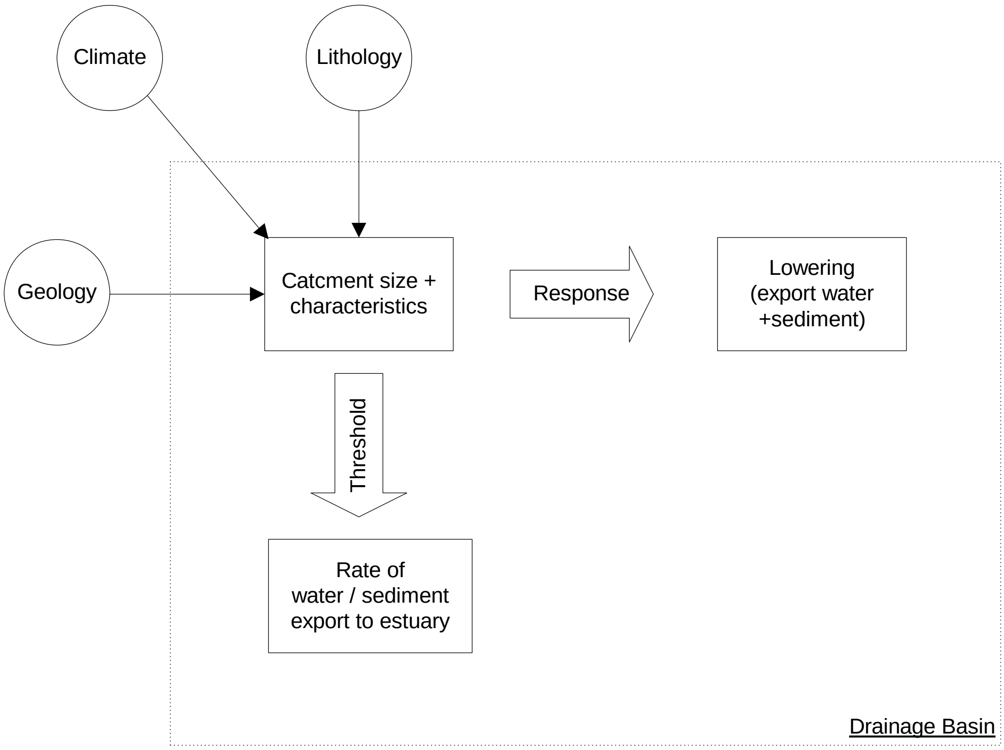
Interaction with other elements - Drainage Basin



Short to medium term system diagram - Drainage Basin



Medium to long term system diagram - Drainage Basin



Appendix L: Behavioural Statement Case Study: Southampton Water

Specific Estuary Name: Southampton Water

Generic Estuary Type: Spit Enclosed

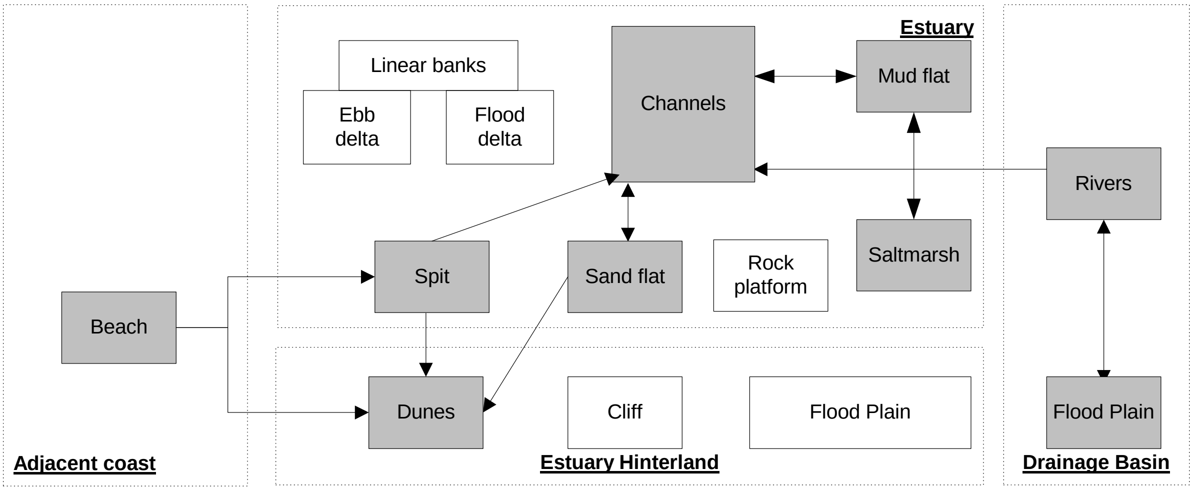


Figure L1. Southampton Water Systems Diagram

General Interactions

Southampton Water possesses a deep relatively straight channel with a spit extending across the mouth from the western side (Calshot Spit). Three rivers flow into the estuary, two towards the head (the Itchen and Test) and one closer to the mouth (the Hamble). Mudflats and saltmarsh occupy the intertidal along the relatively sheltered western side of the estuary, while the eastern intertidal is dominated by a mixture of mudflat and sandflat.

Southampton Water has been heavily influenced by anthropogenic activity. This influence has been mainly in the form of dredging of the channel and reclamation of former areas of intertidal.

Over the longer term, the ability of the estuary as a whole to translate landward in response to relative sea-level rise may be restricted due to a number of constraints on the system (for example, the rising topography in the outer estuary preventing rollover of this section or the constraint at the Redbridge causeway preventing landward migration at this location). It has been suggested that the system may attempt to ‘warp up’ *in situ* to compensate for this inability for landward translation.

Geomorphological Element Behaviour

Geomorphic Element: Spit
Short Term: Calshot spit plays a critical role in controlling the nature of processes occurring over short timescales within Southampton Water. The spit acts to limit the width of the estuary mouth and offers significant protection to the landward main body of the estuary.
Medium Term: The spit is an ongoing sink for coarse sediments, as illustrated by the substantial lobe of material extending from the spit into the Solent. This is taken to indicate that a breach in the spit is not likely in the foreseeable future. The relative stability of geomorphic element over this medium timescale is likely to contribute to the stability of the channel in the vicinity of the mouth.
Long Term: Evidence suggests the existence of the spit since circa 7,000 years BP. However, the spit has exhibited dynamic behaviour over this timescale in the form of periods of extension and breaching. This behaviour is likely to be a response to forcing such as changes in the rate of relative sea-level change, variations in sediment supply and storm incidence.

Geomorphic Element: Channel
Short Term: Flows within the subtidal channel of the estuary are complex due to the nature of tidal propagation in the Solent, with the occurrence of a high water stand within the flood portion of the tide (known as the young flood stand), resulting in two periods of flood currents. The nature of tidal propagation through the channel into the estuary is critical in controlling sediment pathways over tidal timescales. Tides within the channel are ebb dominant with an ebb phase of less than 5 hours and a flood phase of more than 7 hours, although this asymmetry decreases in an upstream direction. An important result of this ebb dominance is the movement of coarse sediments down estuary, resulting in the formation of gravel/sand waves and linear furrows in the outer estuary. However, despite the ebb dominance, fine sediments are imported into the estuary from marine sources (See: Short Term, Mudflats section).
Medium Term: Over this timescale there is a tendency for deposition of sediments within the channel, although the nature of this deposition is spatially variable. Accretion occurs in both the inner and outer subtidal channel, however, this accretion is greater in the inner channel. Dredge channels, berth pockets and docks all act as sediment traps, with deposited material unlikely to be re-eroded. Annual variations in the maintenance dredging requirement within the estuary reflect the variability in the deposition within this geomorphic element. This variation is likely to reflect the variation in supply of sediment to the estuary from both marine and fluvial sources. Charts over the past 200 years indicate that around the mouth of the estuary the subtidal channel is very stable, with deep water maintained close to Calshot spit.
Long Term: The form of the estuary as a whole, and consequently the channel, over Holocene timescales, has been a function of relative sea-level variations and the rate of relative sea-level change. During periods of rapidly rising relative sea-level, the channel has increased in width and length, in line with the estuary as a whole. Equally during lower rates of rise and fall in relative sea-level, the channel is likely to have shortened and narrowed, again in line with the overall estuary form.

Geomorphic Element: Mudflat
Short Term: Flows over the intertidal mudflats over short timescales are dominated by tides, but wave action also plays an important role in enhancing bed stresses. The majority of sediment transport across the intertidal mudflats occurs on 4 or 5 days around spring tides with almost no re-mobilisation of the bed during and around neap tides. Important tidal re-circulation patterns occur over the intertidal mudflats during the young flood stand. When the flood subsequently resumes, flow directions on the intertidal mudflats are directed towards the upper intertidal areas in the vicinity of saltmarsh. This re-circulation provides a mechanism whereby sediments can be transported to the upper intertidal. An important landward flux of fine grained sediments occurs along the intertidal mudflats and is supported by sedimentary evidence. This landward movement of fines into the estuary along the intertidal offsets the seaward directed pathway for coarse grained material within the channel An erosional scarp is observed between the mudflat and saltmarsh, attributable to scour due to waves and the actions of shells that make up the cheniers.
Medium Term: Over the medium terms the intertidal mudflats within Southampton Water are eroding features This erosion makes a significant contribution to the sediment budget. The erosion of mudflats is highly spatially variable, with some areas experiencing a stable plan area but a lowering of levels (such as Hythe to Calshot) with other areas exhibiting less lowering but a landward retreat of the low water line (such as Netley). In general terms the ongoing erosion of this geomorphic element over the medium term is greater in the outer estuary than the inner estuary.
Long Term: In general terms the intertidal areas of Southampton Water have accreted over the Holocene following the flooding of the previous valley to form the modern estuary. Accretion of the tidal mudflats is likely to have occurred in line with a general upward trend in relative sea-level. The extent and character of the intertidal mudflats through the Holocene are likely to have changed in response to variations in the rate of relative sea-level change. General intertidal sedimentation has not occurred at a uniform rate over the Holocene, although there appears to have been sufficient sedimentation to keep pace with past relative sea-level change. Any variations in sedimentation across the intertidal over this timescale are a reflection of variations in the rate of relative sea-level change. For example, periods of low relative sea-level rise (or potentially even a relative fall in sea-level) reflected by low sedimentation rates. Intertidal development over this timescale is also likely to reflect the degree of protection within the estuary at a given time. For example, reflecting variations in the position and form of Calshot spit and hence the degree of protection within the estuary.

Geomorphic Element: SandFlat
Short Term: Sandflats are found predominantly on the more exposed eastern intertidal areas and are hence affected over short timescales more by the occurrence and magnitude of wave events (relative to mudflats).
Medium Term: Intertidal behaviour over decadal timescales within Southampton Water is discussed within: Mudflats, Decadal Change.
Long Term: Intertidal behaviour over Holocene timescales within Southampton Water is discussed within: Mudflats, Holocene Change.

Geomorphic Element: Saltmarsh
Short Term: The tidal re-circulation pattern discussed as occurring over the intertidal mudflats (See: Short Term, Mudlfat) have an important role to play in influencing the behaviour of saltmarshes within certain areas of Southampton Water. As the flood tide resumes following the end of the re-circulation on the young flood stand, flows are directed towards the upper intertidal. This material is then available for deposition on the saltmarsh on the following slack high water. This process therefore provides the mechanism for moving sediment onto the saltmarsh. An erosional scarp is observed at the interface between saltmarsh and mudflat, this is due to scour caused by wave processes. In addition, cheniers occur on the more seaward areas of saltmarsh at Calshot and Hythe. These features can increase the erosion of the underlying surface and therefore can affect the behaviour of this element.
Medium Term: Saltmarsh change over decadal timescales historically has been due to both direct loss due to reclamation and natural changes. The natural changes are less in magnitude but remain significant. In 1870, the ability of Spartina to colonise intertidal mudflats led to the rapid expansion of saltmarsh within the estuary. Accretion rates within the period were up to 20m/yr. Since 1930, this process of saltmarsh accretion began to reverse and this feature became erosional. However, the rate of saltmarsh erosion appears now to be decreasing. In the 1940's the rate of erosion was around 8m/yr. However, this rate has reduced to 0.5m/yr over the past decade. The historic data suggests that if rates of loss are extrapolated, the rate will reduce to zero over the next decade. Evidence suggests that an ongoing process of frontal erosion is occurring along the saltmarsh within the estuary. However, further evidence also suggests that the saltmarsh is not undergoing internal desiccation and the internal channel network would appear to be stable. This supports the view that the observed behaviour is, in part related to the expansion and subsequent die back of Spartina. The records of rates of change over decadal to century timescales, suggests that saltmarshes within the estuary are moving towards a more stable state, restoring the balance in the estuary following the perturbation caused by the rapid spread of Spartina.
Long Term: In common with the observations regarding Holocene changes across mudflat areas, the intertidal areas of Southampton Water, including areas of saltmarsh, have accreted over the Holocene following the flooding of the previous valley to form the modern estuary. Accretion is likely to have occurred on saltmarshes in areas offering a sheltered environment. The rate of accretion across saltmarshes over this timescale is likely to reflect the rate of relative sea-level change and the corresponding supply of sediment.

Geomorphic Element: Drainage Basin/Rivers
Short Term: Fluvial input amounts to approximately 1% of the tidal prism and provides only small amounts of sediment to the estuary. However, over short timescales, the role of the drainage basin as a whole may increase during storms and periods of high fluvial discharge. Suspended sediment concentrations fall towards the head of the estuary and hence short term fluctuations in fluvial inputs are significant in effecting suspended sediment concentrations in these areas. In addition, variations in flows can also be significant due to the influence on stratification and increases in sediment supply during periods of high flows.
Medium Term: This geomorphic element only makes a small contribution to the sediment budget for the estuary. Changes in the contribution of this element may occur as a result of rainfall or catchment changes. However, sediment and flow inputs from the drainage basin are likely to remain small in the context of the estuary.
Long Term: The rivers feeding Southampton Water (Itchen, Test, Hamble) are likely to have been freshwater marsh systems during early Holocene and have oscillated between marine and freshwater conditions during last 6,000 years. The underlying geology of the drainage basin exerts a control on evolution. In the case of Southampton Water, this is chalk that therefore limits the quantity of sediment supply.

Annex L1: Analysis Details

Form of Analysis:	Historical Analysis
Reference:	ABP Research & Consultancy Ltd (2000)
Geomorphic Elements relevant to:	Saltmarsh; Mudflat; Channel.
Behavioural Timescales covered by Analysis:	Medium Term (Decades-Centuries.)

Description of Analysis:

Analysis of historical changes in estuary morphology, including:

1. Analysis assessed changes to estuary form between 1783 and 1996 based on available historical charts and maps.
2. Analysis of saltmarsh changes from 1946 to 1996 at decadal intervals based on aerial photography.
3. Reconstruction of developments in the estuary based on archival evidence

Summary of Results:

- The first major port construction occurred on Southampton Water in the 14th Century and was followed by major development in the mid 19th century.
- Subsequent to this the estuary has been subjected to a series of reclamations and channel deepenings. Analysis noted that the degree of development makes it difficult to distinguish between natural and anthropogenic induced change.
- Analysis from 1783 to 1996, illustrates a pattern of intertidal erosion and subtidal accretion.
- Erosion of the intertidal is spatially variable, whilst the outer subtidal has accreted by a small amount and the inner subtidal has accreted substantially, when annual maintenance dredging volumes are factored in.
- The data indicates narrowing of the intertidal throughout the estuary, albeit at a spatially variable rate. See Table 1 below:

Table 1. Horizontal Movement of Low Water (m/yr)

Location	**1783-1926**	**1926-1932**	**1932-1951**	**1951-1965**	**1965-1996**	**1783-1996**
Netley	-1.2	-9.6	+1.7	-3.5	-2.2	-1.3
Dibden	-0.1	-15	+2	+1.7	-0.9	-0.3
Hythe	-0.5	-9.5	+1.4	+2.3	-0.5	-0.4
Fawley	-0.2	-	-	-	-1.8	-

- Most historical saltmarsh loss in the estuary is noted as being due to reclamation;
- Natural changes in saltmarsh area is less dramatic but significant (Table 2).

Table 2. Rates of Saltmarsh Retreat (m/yr)

Location	**1946-1954**	**1954-1963**	**1963-1976**	**1976-1986**	**1986-1996**	**Average**
Hythe	2.5	1.9	0.2	0.9	0.9	1.1
Eling	1.3	0.4	3.9	1.7	0.7	1.7
All	8	4.3	5.4	3.8	0.5	4.3

- Overall the data suggests that the rate of saltmarsh loss in the estuary is reducing
- This may be a reflection of a return to equilibrium following the spread of Spartina (1880-1930), which was associated with accretion rates of 20m/yr.

Form of Analysis:	Sediment Budget
Reference:	ABP Research & Consultancy Ltd (2000)
Geomorphic Elements relevant to:	Drainage Basin; Saltmarsh; Intertidal (mudflat and sandflat); Cliff; Channel
Behavioural Timescales covered by Analysis:	Medium Term (Decades to centuries)

Description of Analysis:
An indicative sediment budget was compiled from both existing literature and volumes calculated from an analysis of historical data. Given the inherent difficulties in compiling a quantified sediment budget, the analysis highlights the use of the derived figures to establish the relative magnitudes of change.

Summary of Results:
- The quantified sediment budget is presented in Table 1. The overall accretionary balance is assumed to be met via the importing of sediment from marine sources through the estuary mouth.
- Although the main channel of the estuary is ebb dominant, it is thought that fine sediments are transported landward along the margins of the estuary.

Table 1. Sediment Budget

Source	**Sediment Volume (m^3/yr)**	**Notes**
Rivers	- 17,000	Average flow of $30m^3s^{-1}$
Saltmarsh erosion	- 6,000	0.6ha/yr, average height of 1m
Saltmarsh accretion	+ 3,800	Sea-level rise of 2mm/yr
Cliff erosion	- 4,900	Retreat at 0.35m/yr, 2m cliff
Intertidal erosion	- 118,000	From volume change analysis
Intertidal deposition	+ 58,200	From volume change analysis
Subtidal erosion	- 237,800	From volume change analysis
Subtidal deposition	+ 240,700	From volume change analysis
Annual dredging	+ 160,000	Dredging records (±80,000)
Balance	+ 79,000	Equals marine sediment import

Form of Analysis:	Tidal Asymmetry
Reference:	ABP Research & Consultancy Ltd (2000)
Geomorphic Elements relevant to:	Channel; Intertidal
Behavioural Timescales covered by Analysis:	Short Term (within a year)

Description of Analysis:
Various measures used to assess the nature of the tidal wave in Southampton Water in order to determine how any tidal asymmetry may be affecting water and sediment movement.

Summary of Analysis:
- Analysis of the tidal excursion in the estuary clearly illustrates ebb dominance, reducing in an upstream direction
- Analysis of slack durations is more complex, with the results being dependant on the thresholds used. The slack duration asymmetry suggests a location of convergence along the estuary, whereby, ebb dominance upstream and flood dominance downstream results in the convergence of sediment.
- The slack duration is flood dominant upstream until a point at the container terminal, where the duration becomes ebb dominant.
- The location of this reversal (or convergence) moves downstream with an increasing threshold.

Form of Analysis:	Saltmarsh Analysis
Reference:	ABP Research & Consultancy Ltd (2000)
Geomorphic Elements relevant to:	Saltmarsh
Behavioural Timescales covered by Analysis:	Medium Term (Decades to Centuries)
Description of Analysis: Maps from 1996 onwards analysed to asses distribution of saltmarsh species. The results from this analysis were compared with the results from the historical analysis previously described.	
Summary of Analysis: - Spartina became common in Southampton Water from the mid 19th Century and began colonising the intertidal muds resulting in a rapid advance of saltmarsh area. Rates of about 20m/yr occurred. - From 1930, this trend has ceased, replaced by an ongoing trend of erosion. - Analysis of Aerial photos and CASI images suggests that despite the fact that ongoing frontal erosion is occurring, the saltmarsh within the estuary is not subject to internal dissection. - This suggests that the 'die back' of saltmarsh recorded and noted above, may be due to restoration of balance within the estuary or changes in wave climate leading to exposure.	

Form of Analysis: Process Modelling:	Tidal Flows
Reference:	Price and Townend, 2000
Geomorphic Elements relevant to:	Channel; Intertidal
Behavioural Timescales covered by Analysis:	Short Term (Tidal Cycle)
Description of Analysis: - Depth averaged finite difference model used to calculate water levels and flows due to tidal forcing. - Models calibrated and validated against water level and flow data.	
Summary of Analysis: - Unusual flow characteristics identified within the estuary. - Re-circulation of flows observed over the intertidal during the young flood stand, with a null zone in the centre allowing sediment to settle from suspension. - On resumption of the flood tide, the deposited material is re-eroded and moved up the intertidal to supply the upper intertidal and saltmarsh. - This has been identified as a critical mechanism driving sediment transport that can be used to aid the overall understanding of linkages between different elements of the system.	

Form of Analysis:	Holocene Analysis
Reference:	Long, A., Scaife, R and Edwards, E. 1997. Dibden Bay, Southampton Water: Holocene Environmental History University of Durham Report. October 1997.
Geomorphic Elements Relevant To:	Estuary Wide
Behavioural Timescales covered by Analysis:	Long Term (Centuries to Holocene)
Description of Analysis: - Detailed review of existing boreholes, along with a number of new boreholes and cores - Data used to develop understanding of sea-level rise and associated sedimentation over the past 6,000 years	
Summary of Analysis: - Rate of rise of mean sea-level over past 6,000 years found to be generally linear at 1.1mm/year. - Corresponding sedimentation rates found of 1-7mm/year and a noted increase in sedimentation rates due to establishment of *Spartina anglica* within estuary.	

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Appendix M: Behavioural Statement Case Study: The Humber

Specific Estuary Name: The Humber

Generic Estuary Type: Spit Enclosed

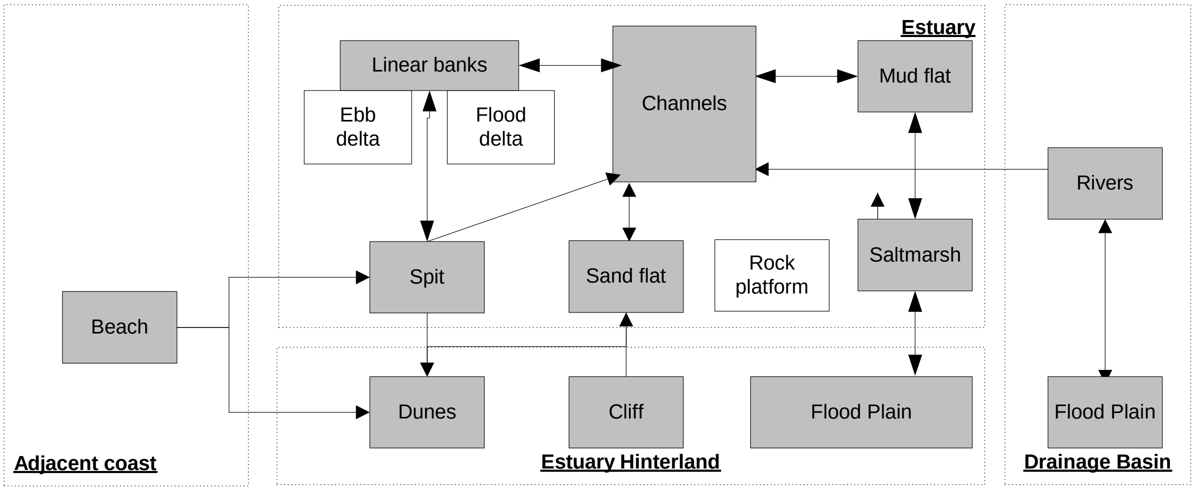

Figure M1. The Humber Systems Diagram

General Interactions

The area around the mouth of the Humber is heavily influenced by the presence of Spurn Head (a sand spit extending across the estuary mouth from the adjacent coastline to the north). Large areas of intertidal mudflats exist in the outer estuary (Spurn Bight and Cherry Cobb), adjacent to the main channel. In addition a further extensive area of mudflat is located at the head of the estuary. Saltmarsh is located, in variable quantities, along both the northern and southern margins of the estuary. Linear banks exist within the channel in the outer estuary, along with sand flats. The Humber also supports several sand dune systems. The estuary has a large fluvial catchment area.

The Humber has been heavily influenced by anthropogenic activities due to port developments and associated industrial activity. The intervention has been mainly in the form of reclamation of areas of upper intertidal and channel dredging. In addition, flood defences have been constructed along parts of the estuary, enclosing reclaimed areas.

Over a decadal scale the estuary has continued to adjust to both changes in relative sea-level and reclamation of large areas of upper intertidal. The estuary is going through a process of 'warping up' to keep pace with relative sea-level rise. Over decadal scales there is evidence of estuary response to the lunar cycle variations.

Over the longer term, there is some evidence that the estuary is translating landward in response to relative sea-level rise. The nature of the estuary's response to longer term changes in relative sea-level will be influenced by the amount of accommodation space that is available for landward migration. Some of this accommodation space is currently retained behind sea walls.

Geomorphological Element Behaviour

Geomorphic Element: Spit
Short Term: Spurn Head exerts an important control on the processes within the Humber. The spit partially constricts the estuary mouth, providing a sheltered environment in its lee (Spurn Bight) within the outer estuary. In addition the spit acts as a pathway for sediment eroded from the Holderness coast to the north during storms that can subsequently be transported into the Humber. In addition to this overall pathway, there is also some evidence from bedforms for a secondary linkage from the root of Spurn (at its northern end) to the 'Binks.
Medium Term: Over decadal timescales, Spurn has historically been held, in terms of its position, by defences. These defences have therefore prevented the feature from responding in an unconstrained manner to forcing conditions, such as changes in relative sea-level or variations in sediment supply. However, these defences are now beginning to fail, allowing the spit to re-align in response to, for example erosion of the Holderness coast to the north and changes in relative sea-level. As the spit re-aligns, there is potential for intermittent breaching, this is greatest at the unprotected northern end, depending on the occurrence and magnitude of storm events capable of removing quantified of sediment. If either storm events or a reduction in supply result in the removal of the protective sand and gravel at the southern end of the spit, it is possible this section may also respond through re-alignment over these timescales.
Long Term: Evidence suggests some form of spit or barrier beach existed seaward of the present day position of the spit at early stages of the Holocene (although not necessarily in a similar form to that seen today). The feature has subsequently rolled back landward. The surficial spit is composed of a volume of blown sand underlain in the northern section by mudflats sediments and till and in the southern section by sand and gravel fronting mudflat sediments and till. Over this longer term, future changes in this feature are likely to involve rollback of this feature as a whole combined with a degree of re-alignment of the northern section of the spit as the Holderness coast erodes and re-aligns.

Geomorphic Element: Linear Banks
Short Term: Middle Shoal is known to exhibit rapid changes, in addition to responding to forcing over longer time interval, for example, response to variations in fresh water flows. Foul Holme Spit illustrates less rapid change, responding to forcing in a more progressive way.
Medium Term: Bed levels around Middle Shoal have been observed to vary on a 14 year cycle, correlating to a similar period cycle in flows. Hydraulic and sedimentary evidence have both indicated a potential circulation cell around Middle Shoal and Foul Holme Spit.
Long Term: The behaviour of this feature over Holocene timescales is difficult to assess. However, it has been suggested that any bank/delta formations may have migrated landward in conjunction with the landward movement of the estuary mouth. Future changes in this feature over long timescales can be expected to involve migration reflecting any movement of the mouth.

Geomorphic Element: Channel
Short Term: The estuary illustrates varying asymmetry with distance along the estuary. Downstream of approximately the Humber Bridge the estuary is ebb dominant. However, to landward, the estuary is flood dominant to a variable point upstream, in the vicinity of Trent Falls. The channel is highly dynamic over short timescales and capable of rapidly responding to change. The location of change varies according to flow conditions. The main subtidal channel in the inner Humber is prone to lateral channel switching in the vicinity of Reed's Island. Detailed analysis of records has revealed that the channel switches from south of Reeds Island into Redcliff Channel happen in response to substantial fluvial flood events, during periods of larger tidal range. Migration of the channel back to north of Reed's Island, is more of a progressive migration. If periods between flood events are long enough, the channel switches to south of Reed's Island. Channel switching over these short time periods can be seen to be a response to fluvial flood events (although the timing of these events relative to tidal cycles may also exert an influence) and therefore the period and nature of these switches is a reflection of the frequency and magnitude of these events.
Medium Term: A number of controls over channel position and migration within the estuary can be identified. In the inner Humber, the Trent Falls training works have restricted the length over which channel switching can occur. While channel migration in the outer estuary is constrained by the underlying till. Over decadal timescales, shorter term variations in channel position may be affected by a longer term trend that could alter the thresholds at which switching is triggered.
Long Term: Over Holocene timescales, tidal waters have progressively occupied and infilled the channel, with periods of stable alignment and periods of migration. The physical constraint of the sill at Hull exerted a significant influence on Holocene development. As relative sea-levels rose to a level above the sill, the inner estuary basin progressively became dominated by tidal rather than fluvial flows.

Geomorphic Element: Mudflat/Sandflat
Short Term: The processes dominating over the intertidal mudflats within the estuary vary according to location along estuary and the degree of exposure. Tidal flows dominate sediment movements and morphological change in sheltered areas of the estuary, with fluvial flows having an increasing influence with distance landwards and wave also exerting an influence in the outer estuary. Sediment movement over the mudflats can vary significantly over a spring-neap tidal cycle and the intertidal is capable of responding to change relatively rapidly.
Medium Term: Detailed analysis of the historical change in intertidal sediment volumes within the estuary reveals a cyclical trend in intertidal volumes that can be related to the 18.6 lunar nodal cycle. Fluctuations over these timescales are superimposed on a longer term trend, whereby the total intertidal area decreased until 1985 and has been increasing since this time. This trend can be further considered in terms of the different sections within the estuary. In the outer estuary, intertidal volumes vary according to a cycle with a degree of correlation to the lunar nodal cycle. This is superimposed on a general decrease in intertidal area since 1956. In the middle estuary, it is difficult to relate the fluctuations in intertidal area to the lunar nodal cycle. Overall, intertidal areas within this section have decreased between 1936 to 1985 and increased thereafter. In the inner estuary, the data illustrates a small increase in intertidal area since 1936, although this cannot be related to the lunar nodal cycle. These detailed assessments of intertidal changes illustrate that there are a number of factors controlling intertidal behaviour in the Humber over decadal timescales, contributing to a complex series of responses. Clearly the lunar nodal cycle exerts an influence together with longer term relative sea-level fluctuations. However, prediction of future intertidal changes in the estuary suggest future reduction in intertidal volumes over decadal timescales
Long Term: Over this longer timescale, the estuary has infilled to keep pace with relative sea-level rise. This response is reflected by deposition of sediments on the intertidal.

Geomorphic Element: Saltmarsh
Short Term: Saltmarshes are mainly influenced by tidal processes with the potential for influence from wave action and fluvial flows depending on location within the estuary. Over these short timescales, channel switching is known to occur in the inner estuary, triggered as a response to fluvial flood events. This process can have an important influence on saltmarsh behaviour, with channel migration resulting in sequences of saltmarsh formation and erosion.
Medium Term: Analysis has suggested that since the early 19^{th} Century the total coverage of saltmarsh within the estuary has decreased. Land reclamation is thought to have made an important contribution to the overall change. More detailed analysis over recent decades has revealed an overall increase in the coverage of saltmarsh within the estuary. The greatest variability was found to occur in the inner estuary, with an increase in coverage in this area. The middle estuary was shown to be relatively stable while the outer estuary demonstrated a loss over recent decades. A number of potential causes can be identified for the high degree of variability in the inner estuary in particular. As noted, saltmarsh in this area will be influenced by channel migration. In addition it is thought that the stabilisation of the channel resulting from the construction of the Trent Falls training works has also resulted in saltmarsh expansion in this area. The losses in the outer estuary are not confined to a specific location, but are a more uniform change over the whole area. This would suggest this is a response to an ongoing estuary influence as opposed to a site specific influence. These outer estuary losses may be related to coastal squeeze under rising relative sea-levels and a hinterland constrained by sea defences. Prediction of future changes in saltmarsh area suggests a reduction over decadal timescales.
Long Term: Over this longer timescale, the estuary has infilled to keep pace with relative sea-level rise. This response is likely to be reflected by deposition of sediments on the intertidal.

Geomorphic Element: Drainage Basin/Rivers
Short Term: High fluvial flows enter the estuary system during winter fluvial flood events. These fluvial flows can exert a significant influence in terms of both channel switching and intertidal processes, with the influence more marked in the inner estuary.
Medium Term: Decadal changes to the influence of the drainage basin on the estuary are influenced primarily by urbanisation affecting run off and potential rainfall changes.
Long Term: Over the Holocene evidence exists for the substantial re-alignment of the rivers within the drainage basin.

Annex M1: Analysis Details

Form of Analysis:	Tidal Asymmetry
Reference:	ABPmer (2004a)
Geomorphic Elements relevant to:	Channel; Intertidal
Behavioural Timescales covered by Analysis:	Short Term (within a year)
Description of Analysis: - A number of parameters were calculated to determine the characteristics of the tidal wave within the Humber focussing on tidal asymmetry and its influence on water and sediment movements in the estuary. - The parameters calculated were as follows: 1. Dronker's Ratio (indicator of overall asymmetry); 2. Slack gradient (indicator of asymmetry as it effect fine sediments; 3. Tidal Excursions (difference between flood and ebb excursion above a threshold to indicate movement of coarse sediments).	
Summary of Results: - The Dronker's ratio indicates spatially variable pattern of asymmetry along the estuary. The first 10km moving upstream from Spurn are ebb dominant, the following 25km upstream are flood dominant, upstream of this point the estuary returns to ebb dominance for 10km before returning to strong flood dominance in the upper reaches - Analysis of the slack gradients suggests flood dominance to a point 85km upstream of the mouth. Slack durations are also flood dominant to a similar point up estuary. In addition there is an increase in slack duration flood dominance around the mouth - Tidal excursions are ebb dominant throughout the estuary, increasing upstream.	

Form of Analysis:	Historical Analysis
Reference:	ABPmer (2004a)
Geomorphic Elements relevant to:	Intertidal; Subtidal
Behavioural Timescales covered by Analysis:	Medium Term (Decades to Centuries)

Description of Analysis:

- Detailed historical Analysis undertaken over several phases, based on a comprehensive historic bathymetric dataset.
- 22 Bathymetric datasets used in total.
- Analysis undertaken of changes to estuary volumes (1936 to 2000) (total volume, intetidal volume, subtidal volume and channel volume) and changes in intertidal area (1936 to 2000) (outer, middle and inner estuary).

Summary of Results:

- In terms of volumes, the analysis showed a long term trend of increasing total volume. Variations in this trend can be related to variations in tidal range associated with the lunar nodal cycle (18.6 years) with a phase lag of between 2 and 5 years.
- Intertidal volumes also show a long term trend.
- Subtidal volumes appears to be relatively stable in the long term.
- In terms of intertidal areas, the changes over time for different reaches within the estuary are shown in Table 1 below.
- There is a general trend of decreasing area in the outer estuary since 1956. There is also a degree of correlation between outer estuary intertidal volumes and the lunar nodal cycle, with a phase lag of around 2 years;
- In the middle estuary, the intertidal area decreased from 1936 to 1985 and has increased thereafter.
- There is a general trend in the inner estuary of a small increase in intertidal area with time.
- In terms of total area, the intertidal decreased until 1985 and has increased since.

Table 1. Historical Changes in Intertidal Area

Year	Outer-north (ha)	Outer-south (ha)	Outer (Combined) (ha)	Middle (ha)	Inner (ha)	Total (ha)
1936	3790	1512	5302	2945	1686	9933
1940	3800	1451	5251	3154	1172	9577
1946	3700	1263	4963	2872	1660	9494
1950	3586	1284	4870	2773	1829	9472
1956	3835	1520	5355	3148	1780	10283
1960	3872	1467	5339	2797	1891	10028
1966	3899	1403	5302	2563	1831	9696
1970	3787	1343	5130	2427	1849	9407
1976	3952	1394	5347	2401	1765	9513
1980	3906	1403	5308	2550	1788	9646
1986	3794	1371	5164	2171	1881	9216
1990	3816	1205	5021	2397	1992	9410
1993	3870	1286	5156	2472	1957	9584
1997	3904	1315	5220	2538	2230	9988
1998	3878	1304	5182	2623	2214	10019
1999	3795	1283	5079	2562	2153	9795
2000	3897	1249	5146	2566	2135	9847

Note: Outer estuary - Spurn to Stallingborough; Middle estuary - Stallingborough to Hull; Inner estuary - Hull to Trent Falls

Form of Analysis:	Saltmarsh Analysis
Reference:	ABP Research & Consultancy Ltd (1996b); Pethick (1994)
Geomorphic Elements relevant to:	Saltmarsh
Behavioural Timescales covered by Analysis:	Medium Term (Decades to centuries)

Description of Analysis:

Analysis of saltmarsh area change over time with consideration to spatial variations. Two different analysis using different data:

1. Pethick (1994): based analysis of OS maps
2. ABP Research & Consultancy Ltd (1996): based on analysis of aerial photographs

Summary of Results:

The results from the two analysis in terms of the spatial and temporal variations in saltmarsh area are presented in Tables 1 and 2.

Table 1. Temporal Variation on Total Saltmarsh Coverage Within the Humber Estuary

A. Pethick (1994)	
Year	**Area (ha)**
1824	1826
1977	1148
B. ABP Research & Consultancy Ltd (1996)	
1976	590
1995	627

Table 2. Spatial Variation in Saltmarsh Coverage within the Humber Estuary (ABP Research & Consultancy Ltd, 1996)

Location	**Area (ha) 1976**	**Area (ha) 1995**	**Change**
Inner	168	226	+58
Middle	64	67	+3
Outer	357	333	-24
Total	590	627	+37

- The Pethick (1994) analysis records an overall decrease in area of 678ha. This notes the importance of the effects of land reclamation in these figures. The role of channel migration is also noted as being of importance;
- Differences between the 1976 and 1977 data is attributed to the different data sources and relatively higher accuracy of aerial photos.
- In the ABP Research & Consultancy Ltd (1996b) dataset there is a net increase of 37ha of saltmarsh over the 20year period.
- The greatest change was in the inner estuary, with important locations including: Winteringham Haven, Whitton Middle Sands and Read's Island.
- The middle estuary appears stable while there is a net reduction in the outer estuary, attributed to a uniform loss along this part of the estuary.

Form of Analysis:	Channel Migration in Inner Estuary
Reference:	ABPmer (2003a); Haigh *et al* (2004); University of Newcastle (1999)
Geomorphic Elements relevant to:	Channel; Intertidal
Behavioural Timescales covered by Analysis:	Medium Term (decades to centuries)

Description of Analysis:

- A variety of studies have investigated the migration of the main channel in the inner Humber. This has generally consisted of various analysis of historical bathymetric data

Summary of Results:

- Observations of bathymetric surveys showed that 3 distinct channel positions occur between Brough and Hessel, as follows:

1. A northern route through the Redcliff Channel to the north of Read's Island (State 1).
2. A middle course through the area of Redcliff Middle Sand, along the northern edge of Read's Island (State 2a)
3. A southern course, beneath Read's Island (State 2b) through the Ancholme (State 1).

- When the channel lies to the north of Read's Island, a gradual migration occurs towards the south of the island. From the southern side of Read's Island, the channel then switches to the north side of the estuary, and the cycle recommences.
- The timings of previous channel states and switches can be seen in Figure 1 below

Table 1. Timings for the State of the Thalweg (ABPmer, 2003a)

State 1	**State 2a**	**State 2b**
-	1912-1921	1922-1930
1931-1932	-	-
1936-1937	1947-1968	1969-1976
1977-1982	1983-1991	1992-1993
1994-1999	2000-2002	-

- Previous studies have shown that sustained periods of higher flows are required to cause a change. These flows need to coincide with large (spring) tidal ranges so that, at low water the significant of the flows are greater.

Form of Analysis:	Sediment Budget
Reference:	Townend & Whitehead (2003)
Geomorphic Elements relevant to:	Drainage Basin; Channel; Cliffs; Saltmarsh; Intertidal; Adjacent Coast..
Behavioural Timescales covered by Analysis:	Medium Term (Decades-Centuries.)

Description of Analysis:

- A variety of sources of evidence are used to quantify the inputs to the sediment budget for the Humber
- An upper, lower and typical value for each input is quantified.

Summary of Results:

- The concentration and densities for each input used to compile the sediment budget are presented in Table 1 below. The net sediment budget is illustrated in Figure 1.

Table 1. Summary of Sediment Budget Estimates (Dry Solids)

Variable	**Rate (m^3/yr)**	**Conc^n (mg ml^{-1})**	**Density (kg m^{-3})**	**Dry Solids Estimate (t/tide)**		
				Typical	**Lower**	**Upper**
Fluvial Input	7.9×10^9	30		335	70	990
Sus. Load in Est.	-	330-1900		1.2×10^6	0.6×10^6	3.6×10^6
Erosion from cliffs	3900		1800	7	1	16
Supply to saltmarsh	1.26×10^4		1400	11	4	30
Deposition on intertidal	2.69×10^5		1350	200	120	340
Deposition on subtidal	1.91×10^5		1550	230	80	380
Tidal flux at mouth	$0.8\text{-}1.5 \times 10^9$	200-1000		1.2×10^5	0.8×10^5	1.6×10^5
Dredging in docks/ berths	4.96×10^6		1250	2580	1030	4130
Humber channel dredging	2.36×10^6		1550	2860	570	5130
Output from Holderness	3.12×10^6		1750	5200	4400	6700

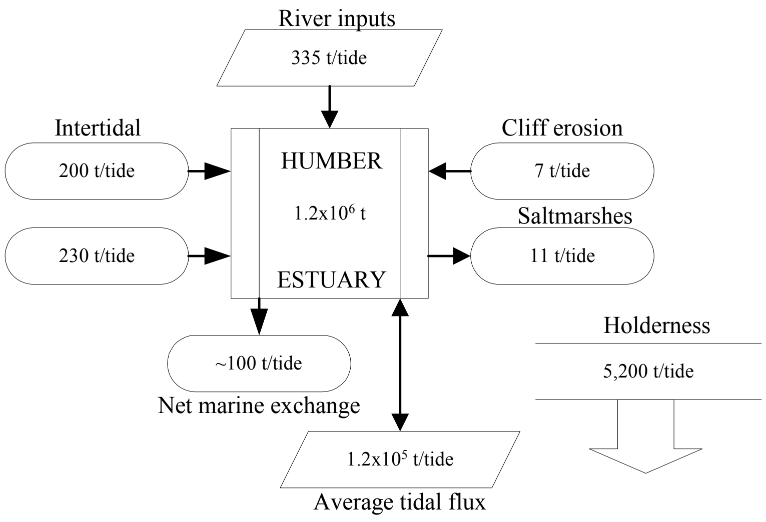

Figure 1. Schematic Diagram of the Net Sediment Budget Model for the Humber Estuary

- The net marine exchange in the net sediment budget is utilised to achieve a balance, suggesting a small marine import of 100t per tide. Although it is noted that the net flux is difficult to calculate or compute with any degree of accuracy.
- The net budget provided is used to indicate a number of key points: 1. The sources and sinks are smaller than the suspended load and 2. The net marine and fluvial exchanges are smaller than the average tidal flux.

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